Development of a land use-based spatial water requirements model for the Berg Water Management Area

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2017

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In fulfilment of the requirements for the degree Master of Science in Geomatics

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Acknowledgements

I would like to thank my mother and sister for their continuing support throughout this project.

I would like to thank the persons involved in the project team for their support and insights. Special thanks to Claire Pengelly, Helen Seiler, Nadine Methner, Professor Mark New, and Associate Professor Julian Smit (supervisor on this project, without whom I would likely not have been able to participate in this initiative).

I would also like to thank Jaco Human of WorleyParsons, Anton Sparks and Dr James Cullis of Aurecon Group, Dr Mike Wallace of the Department of Agriculture (Elsenberg), and Dr Chris Jack and Pierre Kloppers of the Climate Systems Analysis Group at the University of Cape Town for their input and assistance in obtaining invaluable data.

Lastly I would like to thank the Water Research Commission for funding this project and GreenCape and the African Climate and Development Initiative for their guidance and assistance throughout.

Abstract

This study was conducted to investigate the requirements for the spatial modelling of current and future water demand in the Berg River Water Management Area in the Western Cape of South Africa in order to produce a prototype model from which annual water requirements could be computed and spatially visualised. To accomplish this the spatial distribution of water demand within the study area was first investigated. The data required to perform spatial water demand modelling of diverse land uses and socio-economic activities were evaluated. Finally, the question of improving spatial water demand modelling at the catchment scale was considered from both a systems design and a technical perspective.

The resulting model consists of two main modules; one performing a rudimentary monthly soil water balance to obtain monthly and annual irrigation requirements, and another applying preconfigured determinant layers derived from land use to town zone layers in order to determine annual urban water use intensities per areal unit. The resulting model prototype follows a sequential workflow based on a series of components that combine to produce a spatial overview of water use intensity within the study area. Water demand was found to be predominantly irrigated agriculture in the upper reaches of the Berg (mainly wine grape) and was found to be dominated by intensive industrial users in the central and lower reaches. The model was designed so that new data could be introduced in order to expand the system where required, as well as allowing for updated datasets to be incorporated as they become available.

Due to the uncertainties inherent in the modelling and approximation of real world phenomena, the importance of establishing a set of structured, stable, predefined user requirements and system specifications were noted as a fundamental requirement for improving model development and design efficiency and ensuring model validity. It was further found that incorporating additional datasets, covering parameters related to the system, may serve to improve model accuracy, but could easily lead to compounded errors if not correctly parameterised or adequately validated.

Contents

List of Tables

List of Figures

Acronyms

BCC-CSM1-1	-	Beijing Climate Center Climate System Model
BNU-ESM	-	Beijing Normal University Earth System Model
CanESM2	-	Canadian Earth System Model
CAPE	-	Cape Action Plan for People and the Environment
CERES	-	Crop Environment Resource Synthesis Model
CMIP5	-	Climate Model Intercomparison Project
CNRM-CM5	-	The Centre National de Recherches Météorologiques General Circulation Model
CoCT	-	The City of Cape Town
CROPWAT	-	The United Nations Food and Agriculture Organisation's crop irrigation demand model
DEA&DP	-	The Department of Environmental Affairs and Development Planning
DED&T	-	The Department of Economic Development and Tourism
DoA	-	The Department of Agriculture
DSS	-	Decision Support System
DSSAT AEGIS/WIN	-	Decision Support System for Agrotechnology Transfers Agricultural and Environmental Geographic Information System for Windows
DWA	-	The Department of Water Affairs
DWAF	-	The Department of Water Affairs and Forestry
DWS	-	The Department of Water and Sanitation
ENSO	-	El Niño Southern Oscillation cycle
ER	-	Effective Rainfall
ESRI	-	Environmental Systems Research Institute
ET0	-	Reference Crop Evapotranspiration
FAO	-	The United Nations Food and Agriculture Organisation
FGOALS-s2	-	The Flexible Global Ocean-Atmosphere-Land System model, Spectral Version 2
GCM	-	General Circulation Model

GFDL-ESM2G	-	The National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory's Earth Systems Models with General Ocean Model
GFDL-ESM2M	-	The National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory's Earth Systems Models with Modular Ocean Model
GIS	-	Geographical Information System
GISAREG	-	A GIS-coupled version of ISAREG
Ha	-	Hectares
IB	-	Irrigation Board
ISAREG	-	A computer programme for parameterisation of irrigation requirements, using the FAO concepts and methodology.
Kc	-	Crop Factor, also known as Crop Coefficient
m^3	-	Cubic Meter
m^3/a	-	Cubic Meter per Annum
$m^3/c/a$	-	Cubic Meter per Capita per Annum
MAUP	-	The Modifiable Areal Unit Problem
MIROC5	-	The Model for Interdisciplinary Research on Climate
MIROC-ESM	-	The Model for Interdisciplinary Research on Climate's Earth System Model
Mm^3	-	Million Cubic Meters
MRI-CGCM3	-	The Japanese Meteorological Research Institute's Coupled Global Climate Model
PE	-	Potential Evapotranspiration
RCP45	-	Representative Concentration Pathway in which emissions peak around 2040, then decline
RCP85	-	Representative Concentration Pathway in which emissions continue to rise throughout the 21st century
RMSE	-	Root Mean Square Error
SANBI	-	South African National Biodiversity Institute
SST	-	Sea Surface Temperature
UAW	-	Unaccounted-for Water

UNESCO	-	The United Nations Educational, Scientific and Cultural Organisation
USDA	-	The United States Department of Agriculture
WAAS	-	The Department of Water Affairs' Water Availability Assessment Study
WARMS	-	The Department of Water Affairs' Water Authorisation Registration Management System
WCWSS	-	The West Coast Water Supply System
WFDEI	-	WATCH-Forcing-Data-ERA-Interim - A meteorological forcing dataset extending into early 21st C (1979 – 2012). Eight meteorological variables at 3-hourly time steps, and as daily averages
WMA	-	Water Management Area
WRC	-	The Water Research Commission
WRSM	-	The Department of Water Affairs' Water Resource Simulation Model
WSA	-	Water Services Authority
WUA	-	Water Users Association

Chapter 1: Introduction

1.1 Problem Statement

The Western Cape Province is situated in a region expected to experience physical water scarcity in the near future as a result of climate change (UNESCO, 2012). As a result more and more studies are focussing on determining the nature of water demand in various sectors throughout areas that are at risk of decreased supply (DWA, 2012; DWA, 2013; Pegram & Baleta, 2014; DWS, 2014; DED&T, 2015a).

Fauchereau *et al*. (2003) found that rainfall across Southern Africa has been experiencing increasing interannual and interseasonal variability during the 20th century, especially since the late 1960s, and that droughts are becoming more intense and widespread, with an increase in statistical correlation between rainfall anomalies in Southern Africa and the El Niño Southern Oscillation (ENSO) cycle.

The influence of a global oceanic-atmospheric circulation modification event on local climate is known as a teleconnection. Whereas cold sea surface temperatures (SST) in the southwest Indian Ocean are normally associated with drought conditions over Southern Africa, it has been shown that post-1970 ENSO events, embedded in a relatively warm Indian Ocean SST background, have caused below average rainfall over large parts Southern Africa (Richard *et al.,* 2001).

It is believed that the increased teleconnection phenomenon may lead to periodic droughts of greater intensity and longer duration compared with sporadic rainfall caused by local SST anomalies (Richard *et al.,* 2001). It is therefore important to consider the socio-economic implications of water requirements relative to the assurance of supply, as global oceanic and atmospheric changes may alter the frequency and intensity of rainfall disruption, causing more frequent and more intense droughts.

The Berg River is the main supply of freshwater for domestic water users in the Cape Winelands and West Coast regions (DWA, 2012) which, together with its dams and a series of canals and pipelines, are known as the West Coast Water Supply System (WCWSS). The WCWSS provides domestic, commercial and agricultural users with their share of a total system yield of 570 million cubic meters of water per year, with a 98% assurance of supply

(DWA, 2012). This means that supply is estimated to be inadequate once every 50 years or so (DED&T, 2015b).

It was estimated that the total water abstracted from the WCWSS during the 2014/2015 financial year for urban (domestic and industrial) use, including river losses, amounted to just over 377 million m^3/a (DWS, 2015b), although current allocations from the system amount to 584 million cubic meters per year (DED&T, 2015a), making the WCWSS an over allocated system. This has led to concerns about the constraining effects of water unavailability on local economies (Pegram & Baleta, 2014).

The seasonal nature of precipitation and associated runoff which feeds the Berg River and its tributaries represent a vulnerability in the system as a whole. In the event of below average rainfall persisting for more than one wet season the supply of water to users within the catchment may be compromised (Pegram & Baleta, 2014). For this reason it is of great importance to understand the temporal and spatial nature of water use within the study area, in order to inform new strategies that are currently under consideration by local authorities, including the construction of desalination plants (Blersch & Du Plessis, 2014) and reuse of waste water (DWAF, 2007b).

Managing water resources to safeguard local economic growth implies careful monitoring of both supply and demand (Pegram & Baleta 2014). Current rates of urbanisation and population growth in the Western Cape, and particularly in Saldanha Bay, have been indicated as playing a significant role alongside climate change in influencing future water demand (Tadros *et al.,* 2005; DED&T, 2015a). Water availability is increasingly being identified as an inhibitor of economic growth (Tadros *et al.,* 2005; Pegram & Baleta 2014)

Water use data at the catchment scale are captured in a variety of ways, depending on the location of the user, the nature of the source and the intended use of the data. Distributed data ownership complicates data gathering and without clear data creation guidelines can lead to redundancy, excessive heterogeneity and inconsistencies in quality and completeness (DWA, 2013).

Water resource management requires a thorough understanding of the supply operations, demand landscape and strategic policy factors involved (RSA, 1998; Lévite *et al.,* 2003; Tadros *et al.,* 2005). Stakeholders often rely on data analysis performed by experts to inform their decision making (DWA, 2013; Pegram & Baleta 2014). The use of decision support systems for operational management has allowed stakeholders to more easily navigate problems with a high degree of complexity (Rauscher, 1999; Tadros *et al.,* 2005).

This investigation aims to spatially simulate the current and future water demand within the Berg Water Management Area, excluding the City of Cape Town and areas supplied by the Overberg Bulk Water Services Provider in order to render water requirements at different levels of spatial aggregation.

1.2 Research questions

1. What is the spatial distribution of water demand within the study area?
2. What data are needed in order to perform spatial water demand modelling of diverse land uses and socio-economic activities?
3. How can spatial water demand modelling at the catchment scale be improved?

Aims: to design and build a prototype spatial water demand model from which the current and future consumptive water demand of major socio-economic activities can be determined and spatially mapped, based on currently available population, land use and climate data.

1.3 Objectives and Aims

1. To design a water requirements model in order to assist in visualising the spatial distribution of water demand in the study area,
2. To use existing data to derive current water use and predict short and medium term future water requirements for major socio-economic activities drawing on both surface and groundwater within the study area,
3. To validate the resulting current and future water demands against existing estimates and predictions, and

To produce a prototype spatial water requirements model as proof of concept from available data sources.

1.4 Organisation of the Document

Chapter 1: Introduction

Essential problem definition and presentation of aims and objectives for research project.

Chapter 2: Literature Review

A look at the various concepts and activities related to water resource modelling and Geoinformation Systems (GIS) in order to place the project in its academic context.

Chapter 3: Study Area

An introduction to the area of interest for this study and a discussion of various aspects related to water supply and demand within it.

Chapter 4: Data

A discussion of the data required for this project and the acquisition and preparation thereof.

Chapter 5: Methodology

A discussion of the proposed methodology for this project.

Chapter 6: Results and Discussion

A discussion chapter with emphasis on the results and discussions stemming from the project findings.

Chapter 7: Conclusions and Recommendations

A concluding chapter consisting of conclusions drawn and recommendations based around the findings generated from this project.

Chapter 2: Literature Review

From inception to implementation, modelling spatial phenomena requires a well-structured and pragmatic approach (Ruparelia, 2010; Forsberg & Mooz; Maidment, 1996). At the outset the feasibility of a project may easily be overstated or oversimplified, while unforeseen complications may arise during the unfolding of the project that may impact the value and cost of the project, as Hofstadter's Law notes (Hofstadter, 1980).

The process of spatially simulating real world phenomena follows a series of steps in order to produce a valid abstraction within a mathematical environment (Requicha, 1980; Fonseca *et al.,* 2002a; Gomes and Velho, 1995). An important consideration when performing spatial abstraction is the decision of which data structure to use, as the discrete and continuous data structures each possess unique characteristics, as well as potential advantages and disadvantages (Openshaw & Taylor, 1979; Requicha, 1980; MacEachren, 1994; Eicher & Brewer, 2001; Dark & Bram, 2007). Once the abstraction process has been completed, a variety of approaches may be followed in model construction, including the use of visual programming languages (Dobesova, 2011).

Water requirements can be modelled using a variety of approaches and at various levels of spatial and temporal aggregation, depending on the application of the research and the available resources. The most rigorous and complete method for evaluating water use is the water foot-printing approach, which factors in usage of surface and groundwater sources, intercepted rainwater, as well as water used to dilute contaminants (Hoekstra *et al.,* 2011).

Hydrological modelling of river systems in order to investigate water supply, quality and usage is facilitated by geo-information systems and the rise in the popularity of spatial data as a tool for decision making. Hydrological modelling has been used to investigate the impact of existing water use, as well as that of predicted future water use and climate change on water resources (Maidment, 1996; Arnold *et al.,* 1998; Adbelfattah *et al.,* 2009; Praskievicz & Chang, 2009).

This chapter outlines some common themes and approaches related to spatial modelling and water requirements analysis. The processes of systems design, cartographic abstraction and model construction are investigated, along with conventional water related analysis and modelling techniques.

2.1 Water Foot-Printing as a Metric of Water Use: Principles and Applications; Benefits and Limitations

Water footprint accounting allows us to answer the fundamental question: what is the volume of water consumed by man over a specified period of time, within a specific region or for a specified set of activities? A water footprint therefore essentially describes direct and indirect consumption of freshwater in terms of volume over time, relative to the human population and its activities within a given area (Hoekstra *et al.,* 2011).

There are three aspects to water footprints, namely blue, green and grey water use. Blue water footprints refer to any fresh surface or ground water that is consumed throughout the supply chain of a product or by people, where consumption refers to all water that is removed from the available surface or groundwater body via incorporation into a product, direct consumption, evaporation, return flow to another catchment or return flow directly into the ocean (Hoekstra *et al.,* 2011; Mekonnen & Hoekstra, 2011).

The green water footprint refers to the consumption of rainwater by plants, intercepted before it reaches a blue water resource. In other words, green water is rainwater intercepted before runoff can reach tributaries or groundwater recharge can take place (Hoekstra *et al.,* 2011; Hoekstra & Mekonnen, 2012). This implies that water is absorbed and consumed from soil by plants and other organisms before it reaches blue water resources, such as rivers or aquifers.

A grey water footprint is a measure of the volume of freshwater required to dilute any pollutants in order to comply with established water quality standards (Hoekstra *et al.,* 2011), and takes the form of outflows.

Water foot-printing differs from traditional analysis of water abstraction in three respects (Hoekstra *et al.,* 2011):

1. Return flows are not considered part of blue water consumption in water foot-printing.
2. Water foot-printing is not restricted to blue water consumption, but includes green and grey water consumption.
3. Water foot-printing takes into account direct as well as indirect water use.

Water foot-printing therefore provides an insight into both water consumption and water pollution.

For the purposes of this study, a generalised overview of consumptive blue and green water use was investigated.

Water foot-prints may be estimated for an isolated step within a larger production process, or for an entire product. It is also possible to investigate the water footprint of a consumer or class of consumers, or for a specially delineated region (Hoekstra *et al.,* 2011). This study focussed on the administrative region known as the Berg Water Management Area, excluding the City of Cape Town and areas supplied by the Overberg Bulk Water Services. Specifically, the focus of this project was to estimate the water requirements of all activities currently or potentially using water that would otherwise be available to the West Coast Water Supply System.

An important question regarding the extent of water foot-printing analysis is that of spatiotemporal definition (Hoekstra *et al.,* 2011). This refers to the specific levels of detail of the data used in terms of temporal scale and spatial scale. Three main levels of spatiotemporal definition have been described (*Table 2.1*) (Hoekstra *et al.,* 2011)

Table 2.1: Various levels of spatiotemporal definition of water foot-printing analyses, adapted from Hoekstra et al., 2011.

	Spatial Definition	**Temporal Definition**	**Source of Required Data and Water Use**
Level A	Global Average	Annual	Available literature and databases on typical water consumption and pollution by product or process.
Level B	National, Regional or Catchment-Specific	Annual or Monthly	As above, but use of nationally, regionally or catchment specific data.
Level C	Small Catchment or Field-Specific	Monthly or Daily	Empirical data or (if not directly measurable) best estimate on water consumption and pollution, specified by location and over the year.

Water use may be direct or indirect, as in direct consumption by a particular consumer, or water that is embedded within the manufacturing processes of a product consumed by the same consumer (Hoekstra *et al.,* 2011). Indirect water footprints might include the water footprint of labour, transport and of various other inputs into the production chain of a product, such as processed raw materials, components and packaging, as well as energy production (Hoekstra *et al.,* 2011).

It is therefore understandable that the inclusion of the indirect water use in the water foot-printing analysis may have a significant effect on the overall water footprint of a product or consumer. However, as the scope of this project pertains to direct abstraction from a single source (the Berg River), indirect or virtual water consumption was not included in the analysis.

2.2 Hydrological Modelling

Spatial modelling of water requirements usually takes a specific focus, depending on the scale and extent of the study or purpose of the model. Spatial models simulating surface runoff (Dawson & Wilby, 2001), groundwater recharge through percolation (Batelaan & De Smedt, 2001), soil erosion (Mitasova *et al.,* 1996), evaporation from the soil surface (Arnold *et al.,* 1998), point and nonpoint source pollution (Di Luzio *et al.,* 2004) and soil salinity (Adbelfattah *et al.,* 2009), are experiencing increasing development and use around the world today.

Hydrological models have been defined as simulations of all aspects of surface and groundwater flow based on mathematical abstractions of physical laws within a spatial and temporal context (Maidment, 1996). Standalone hydrological models are designed for the purpose of determining the yield within a specific catchment or river basin, but can also be used for exploring the effects of local land use on water quality or for use in conjunction with other models, such as irrigation requirement models (Arnold *et al.,* 1998). These models usually feature specific groundwater modules which allow for the effects of seepage and infiltration to be simulated, representing the interactions between surface water and groundwater (Arnold *et al.,* 1998).

At the third International Conference on GIS and Environmental Modelling, Maidment presented a ten-step modelling procedure for modelling hydrology using GIS data structures (Maidment, 1996):

1. **Study design:** Definition of the objectives and scope of study, the spatial and temporal extent of the study, the variables to be computed, and the process models required in order to perform the computations.
2. **Terrain analysis:** Use of digital elevation and hydrological data in order to derive catchment and channel network layouts.
3. **Land surface:** Description of soils and land cover/land use.
4. **Subsurface:** Hydro-geologic description of groundwater sources.
5. **Hydrologic data:** Geo-referencing of river flow gauges in order to spatially visualise the time series data derived from their measurements, interpolation of climatic data from observation points onto continuous surface maps.
6. **Soil water balance:** Partitioning of precipitation into evaporation, groundwater recharge and surface runoff; partitioning of chemicals applied to the land surface.
7. **Water flow:** Calculating the movement of surface and sub-surface water, including direction and flow rates.
8. **Constituent transport:** Transport of sediment and contaminants in water as it flows. Computing concentrations and loadings.
9. **Impact of water utilization:** Locating reservoirs, water withdrawals from and discharges into waterways, as well as abstraction from aquifers and calculating their impact on water flow and constituent transport.
10. **Presentation of results:** Developing visual and tabular presentation of the study results in order to convey key insights and aid in decision making processes.

This study focussed mainly on water use, simulating water demand in order to determine the spatial distribution of water requirements throughout the study area. While water demand mapping and hydrological mapping are two distinct processes, there is a significant practical relationship between the two operations (Praskievicz & Chang, 2009). Effective rainfall was used to determine the moisture deficit for irrigated crops in the study area, while abstractions from both surface and groundwater sources were mapped.

2.3 Spatial Modelling of Irrigation Requirements: Approaches and Principles

With the increasing availability of spatial and ancillary data, modelling water requirements both temporally as well as spatially is becoming more and more accessible (Aspinall & Pearson, 2000; Arnold & Fohrer, 2005; Serra *et al.,* 2016). Water requirement simulations are useful for investigating the relationship between irrigation management practices and irrigation demand, as well as to predict future demand with the use of data produced from climate modelling (Arnold & Fohrer, 2005; Leenhardt *et al.,* 2004; Thomas, 2008). Yield reduction and soil salinization have also been investigated in order to track the effects of temporal and spatial variability in management regimes, climate and soils on crop yield and water demand (Thomas, 2008; Forkutsa *et al.,* 2009).

Geographic information systems (GIS) are rapidly becoming central to crop water management and planning due to their convenient facilitation of the integration of spatial data with crop models in order to run nutrient and water cycling simulations for large areas using mapped or interpolated spatial data (Srinivasan & Arnold, 1994; Santhi *et al.,* 2005). As cities expand and industrial activities compete increasingly with agriculture for access to water resources, spatially comparing supply with demand as well as investigating the relative spatial distributions of the impacts of management and resource interventions become increasingly important (Vörösmarty *et al.,* 2000; Diaz *et al.,* 2007).

Crop water requirements can be estimated using a variety of methods. These methods normally rely on a combination of datasets including data describing local climate conditions over a period of time, such as daily minimum and maximum temperatures, rainfall volume and intensity, relative humidity, hours of sunlight and average wind speed, and data pertaining to specific crops and cultivation methods, such as planting date, length of growth stages, irrigation method, leaf area index, rooting depth and planting density. Other data often used include soil type, soil layer water holding capacity, soil layer depth, surface soil albedo, and susceptibility to salinization and nitrogen leaching (Jensen, 1973; Jensen *et al.,* 1990).

For small scale simulations, detailed soil maps and field cropping patterns allow for accurate modelling of the spatial distribution of variability in plant water requirements, as well as the soil water balance that affect plant water availability in the root zone (Leenhardt *et al.,* 2004; Satti & Jacobs, 2004). However, for large scale simulations it becomes difficult to incorporate a large number of heterogeneous datasets into the modelling process, leading to the adoption of generalised datasets (Jensen *et al.,* 1990; Satti & Jacobs, 2004). In this regard GIS has proven exceedingly useful for the management of large spatial datasets due to its specialised spatial data input, storage, analysis and visualisation facilities.

In their study of local and regional water requirements for irrigated agriculture in Parana, Brazil, Heinemann *et al.* (2002) used a crop model coupled with a geographic information system (Decision Support System for Agrotechnology Transfers Agricultural and Environmental Geographic Information System for Windows – DSSAT AEGIS/WIN) to determine irrigation water requirements, annual runoff and annual nitrogen leaching by simulating plant and soil water, carbon and nitrogen balances, and crop growth and development (Heinemann *et al*., 2002).

The models used by DSSAT – CROPGRO and CERES – simulate crop growth and vegetative development in grain legumes and grain cereals, as well as crop and soil water and nitrogen balances (Heinemann *et al*., 2002). The soil water balance was determined at daily time steps coinciding with daily meteorological measurements, and were calculated using the following equation:

$$\Delta S = P + I - E_P - E_S - R - D \qquad (1)$$

where ΔS is the resulting soil moisture, P represents the contribution by rainfall, I presents the water applied by irrigation, E_P and E_S are the evaporation for plant and soil respectively, R is water lost through runoff, calculated using a modified version of the USDA soil conservation service technique, and D is water lost through drainage beyond the root zone (Heinemann *et al.,* 2002).

In their study, Heinemann *et al.* (2002) used the methodology outlined by Priestley and Taylor (1972) for simulating evapotranspiration, using daily solar radiation, maximum and minimum daily temperatures, leaf area index and soil albedo to determine both the water lost through plant evapotranspiration as the well as the water evaporated directly from the soil surface.

Fortes *et al.* (2005) described the use of the GISAREG application as a decision support tool for evaluating various irrigation scheduling practices in the Syr Darya basin, Uzbekistan. The application consisted of the ISAREG irrigation scheduling simulation model coupled with a spatial database administered within a GIS framework (Fortes *et al.,* 2005). The ISAREG model simulated a soil water balance for every cropped field based on precipitation, reference evapotranspiration, total and readily available soil water, soil moisture content at date of planting, and crop-specific factors describing crop development, rooting depth, as well as factors pertaining to the relationship between water stress and crop yield (Fortes *et al.,* 2005).

Two sub-programs, EVAP56 and KCISA, processed input data to determine the reference crop evapotranspiration (ET_0) and the pertinent crop factors, respectively (Fortes *et al.,* 2005). EVAP56 used standard methods of calculating ET_0 as described by the United Nations Food and Agriculture Organisation (Allen *et al.,* 1998). Methodologies were chosen based on the availability of data. FAO-described methods were also used to calculate crop factors for four main growth stages (Fortes *et al.,* 2005; Allen *et al.,* 1998).

Once the relevant factors and reference evapotranspiration rates had been calculated, the ISAREG model initiated a soil water balance simulation in order to determine the availability of soil water relative to the potential evapotranspiration of the crop (Fortes *et al.,* 2005). User-defined irrigation depths and timing were incorporated into the simulation, and a water-yield response factor used to gauge the impacts of relative water stress upon crop yield following methodology described by Stewart *et al.* (1977).

The contribution of ground water to plant evapotranspiration was modelled using water table depth, soil water storage capacity, and other soil attributes that commonly influence capillary action and actual plant evapotranspiration (Fortes *et al.,* 2005).

It is the intention of this study to model irrigation water requirements, using time-series monthly climate data in conjunction with crop factors based on the methodology outlined in the FAO Irrigation and Drainage Paper No 56 (Allen *et al.*, 1998) due to the time proven robustness and general simplicity of the methodology (Pereira *et al.*, 2014). Soil water balance is done to the extent of estimating a moisture deficit resulting from plant evapotranspiration-reduced soil moisture, replenished only by effective rainfall and irrigation. No salinity control or other processes are included in the analysis.

2.4 Past Application of Irrigation Water Requirements Modelling in the Berg Water Management Area

A report was published for the Water Research Commission (WRC) by Pegram and Baleta (2014) outlining the flow of water through the Western Cape economy. The report featured water footprints of representative socio-economic activities within the Western Cape, including primary agricultural production, secondary production within key industrial sectors and services and tourism (Pegram & Baleta, 2014).

In their analysis of agricultural production, Pegram and Baleta investigated deciduous fruit, unirrigated wheat, irrigated wheat, vegetables, citrus and grapes, using climate data from the SAPWAT database (Van Heerden et al., 2009). Climate data from the closest weather stations within each district municipality was used in the calculation of crop water requirements (Pegram & Baleta, 2014).

Crop water requirements (ET_a) are typically calculated as a function of evapotranspiration, which refers to the amount of water lost through the leaves of a plant as it transports moisture upwards out of the soil in which it grows (Mekonnen & Hoekstra, 2011). This is estimated using a crop-specific coefficient (K_c), which indicates the typical basic evapotranspirative rates of a crop, multiplied by a known reference evapotranspiration value (ET_o) indicative of local climate, multiplied by a dimensionless reduction factor between one and zero, which indicates soil water availability (K_s) (*Equation 2*) (Mekonnen & Hoekstra, 2011).

$$ET_a[t] = K_c[t] \times K_s[t] \times ET_o[t] \qquad (2)$$

Once the climate variables were calculated, the effective rainfall for each region was calculated for the duration of the growth cycle of each crop in ten-day intervals (Pegram & Baleta, 2014). Effective rainfall refers to the amount of rainfall that percolates through soil to a plants' root zone. There are numerous methods for calculating effective rainfall, each with its own strengths and weaknesses (Adnan & Khan, 2008).

In their analysis of crop water requirements, Pegram and Baleta (2014) used the USDA Soil Conservation Method (SCM) for estimating effective rainfall, which is the standard method used by the CROPWAT model for calculating effective rainfall. The USDA SCM uses a series of progressive classes, estimating the percentage of effective rainfall, which decreases incrementally, from onset of rainfall even to its completion. The effective rainfall within a region is generally inversely proportional to the rainfall intensity within that region, and the USDA Soil Conservation Method has been found to work well under low rainfall intensity conditions (Adnan & Khan, 2008).

After calculating the effective rainfall, Pegram and Baleta (2014) used the minimum effective rainfall and incremental crop water requirements over the growing period of each crop investigated to determine the corresponding green water use for each ten-day increment. The blue water requirement was found by subtracting the overall green water availability from the overall growth cycle water requirements to determine optimal irrigation requirements, which was then multiplied by a factor indicative of irrigation efficiency, where available (Pegram & Baleta, 2014).

This study calculated monthly irrigation demand for the study area at a field level, deriving irrigation requirements from soil moisture deficits and designated irrigation techniques for each field as a unit of homogeneous irrigation regime. Fifteen different crop types were analysed and six different irrigation types were considered in this study.

2.5 Systems Development Lifecycles and Design Processes

Systems development and software development processes have a strong overlap in that both consist of sequential stages of activity from inception to application (Ruparelia, 2010). Systems development lifecycle models have been mostly developed with the aim of providing a consistent guide for a structured approach to the systems development process. These models usually portray a linear, iterative or combination structure, encompassing feedback and sequential progression throughout the development process (Ruparelia, 2010; Benington, 1956; Royce, 1970; Forsberg & Mooz, 1991; Boehm, 1986; Iivari, 1987).

Key development stages normally include requirements analysis, feasibility study, conceptual design, development, implementation and maintenance (Benington, 1956; Forsberg & Mooz, 1991; Boehm, 1986). There are multiple variations on the theme of systems development life cycles, highlighting different approaches to the problem of complex project coordination and feedback integration (Ruparelia, 2010).

One of the first instances of a sequential systems design life cycle model was the waterfall, or cascade model (Benington, 1956). Subsequent models have followed similar structures highlighting the importance of basing systems design on clearly and explicitly defined user requirements and a thorough understanding of existing infrastructure (Royce, 1970; Forsberg & Mooz, 1991; Boehm, 1986; Ruparelia, 2010). In 1970 Royce modified the cascade model with the addition of feedback arcs, redefining the cascade model from a linear model to a combination of linearity and iteration (*Figure 2.1*).

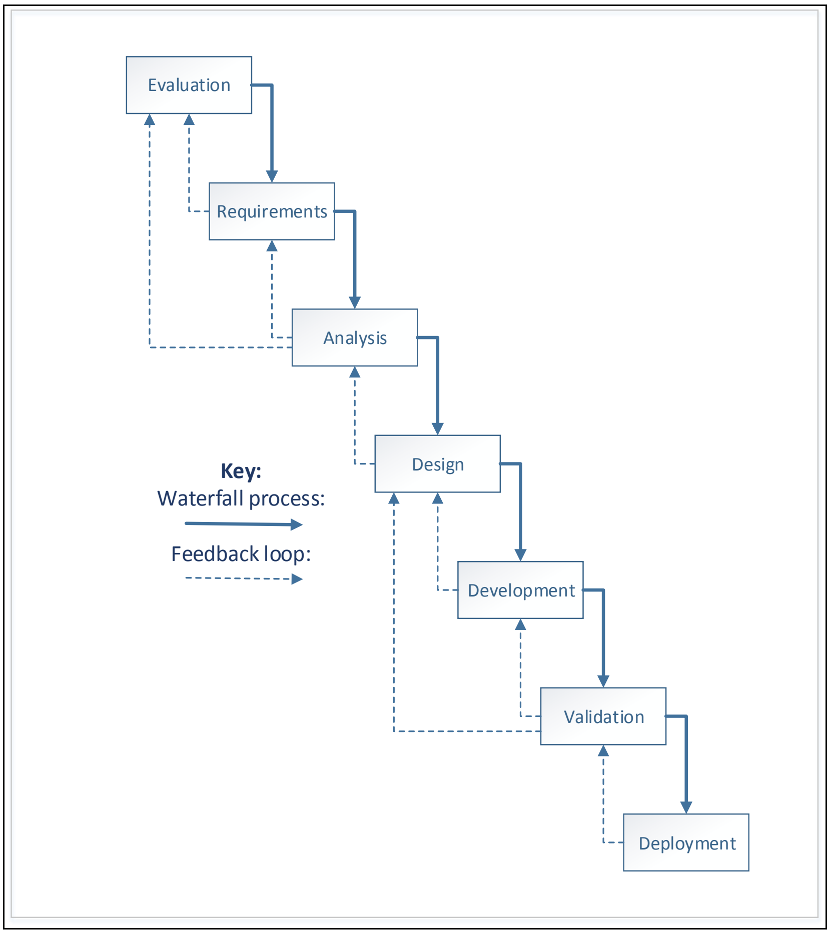

Figure 2.1: Royce's version of Benington's cascade model (adapted from Ruparelia, 2010)

The feedback structure introduced by Royce allowed for periodic review to influence previous stages of project development and took into account the need to bypass the preceding stage entirely in certain circumstances, such as when revelations in the validation step necessitates that the design stage be directly revisited, rather than first returning to the development stage (Ruparelia, 2010).

In addition to the flexible feedback structure afforded by this model, Royce noted that the model also facilitates a rigorous documentation process, and outlined a list of recommended documentation to accompany the full design process (Royce, 1970; Ruparelia, 2010):

- A **Requirements Document** to be produced during the requirements analysis,
- A **Preliminary Design and Interface Design** during the design phase,
- A **Final Design** after successive feedback iterations,
- A **Test Plan** to be developed alongside initial designs, updated with the results of testing and validation during later stages, and
- A **User Manual** with instructions on the use of the final product.

This documentation process gives the user a greater insight into the evolution of the project and the development of the final product, as well as allowing for more detailed review of specific design decisions. This systems design life cycle model has been found to be best suited for developing back-end models and relational databases due to its overall focus on user requirements and general simplicity (Royce, 1970; Ruparelia, 2010).

A more recent model, the V-model (or Vee-model), is comprised of the same premise as the cascade model, but is visually organised to distinguish between the various phases of decomposition and integration (*Figure 2.2*). The model is structured following a similar linearity as the cascade model, but with the second half of the development process - representing the stages of integration and verification from development to deployment - being angled back, so that the individual stages of integration and verification may be coupled with the corresponding stages of decomposition and definition in a comprehensive feedback structure (Forsberg & Mooz, 1991; Ruparelia, 2010). The V-model was specifically developed with large projects in mind, potentially involving multiple contractors, sub-contractors and teams (Forsberg & Mooz, 1991; Ruparelia, 2010).

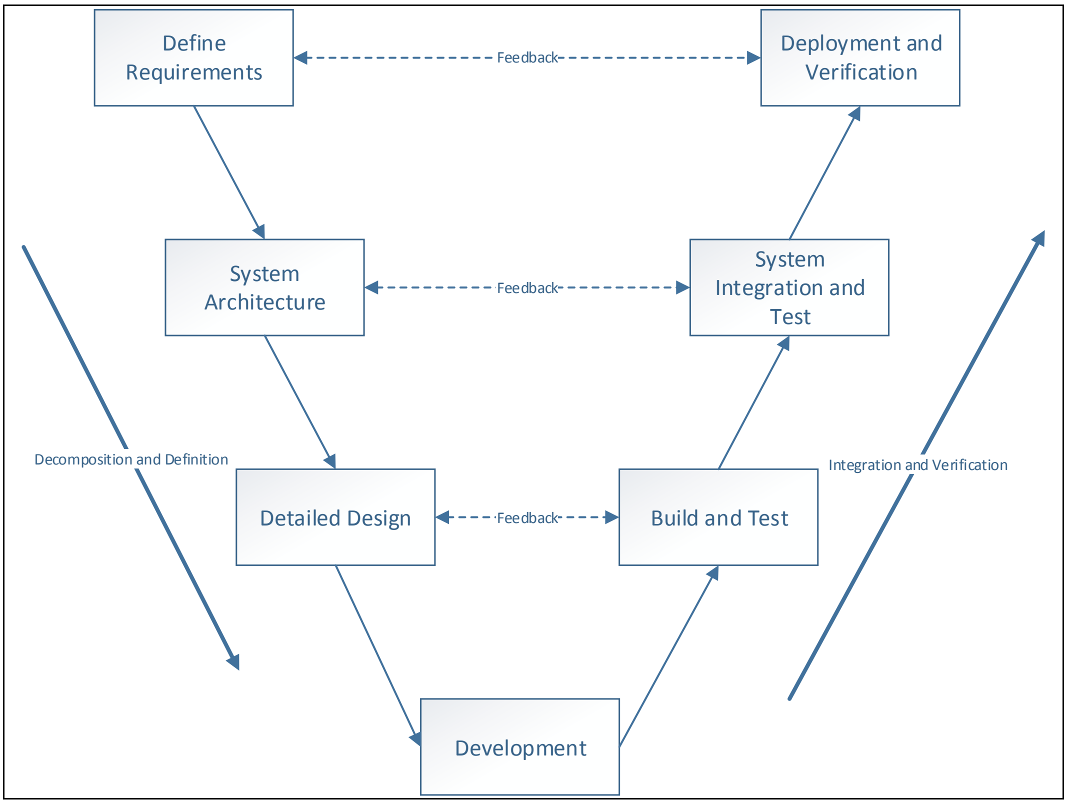

Figure 2.2: NASA's V-model, developed by Forsberg and Mooz (1991); a variation of the cascade model (adapted from Ruparelia, 2010)

The main benefit of the V-model's design is that the symmetrical structure allows for clearly defined verification steps corresponding to each stage both in the decomposition and definition phase as well as in the integration and verification phase to be comprehensively outlined at the outset and amended throughout the development process. This allows for the verification process to be established alongside the development stage at each level (Forsberg & Mooz, 1991).

The V-model can also be visualised in three-dimensional space, where depth – perpendicular to the surface plane – represents the parallel processing of segments or "configuration items" that require their own development specifications, design reviews, testing and reporting (Forsberg & Mooz, 1991). This allows for any large or complex project to be thoroughly broken down into distinct components for better alignment with user requirements and later validation and verification processes, as well as facilitating the simultaneous evaluation of alternative solutions in order to determine the optimum conceptual approach to meet user requirements (Forsberg & Mooz, 1991).

Within the V-model baselines are established throughout project development in order to manage and assess project performance (Forsberg & Mooz, 1991). These include:

- A **User Requirements Baseline** describing the user requirements,
- A **Concept Baseline** describing the essential project concept,
- A **System Development Baseline**, establishing system performance requirements.

These resources allow for a rigorous and well-structured approach to systems design.

With its distinctly modular structure to project development, whereby development and verification steps are paired for greater transparency in the definition of testing and validation parameters, allows for more rigorous initial modelling to take place, as well as facilitating more comprehensive feasibility analysis at the outset (Forsberg & Mooz, 1991).

Another systems design life cycle model that evolved from the cascade model is the spiral model, proposed by Boehm (1986). Where traditional systems design life cycle models follow a mostly linear trend, the spiral model consists of an iterative development process, spiralling out from a central starting point, and moving through sequential stages of progression divided into four main sectors (*Figure 2.3*). The spiral model functions along the vertical and horizontal axes representing "cumulative cost" and "review" respectively (Boehm, 1986).

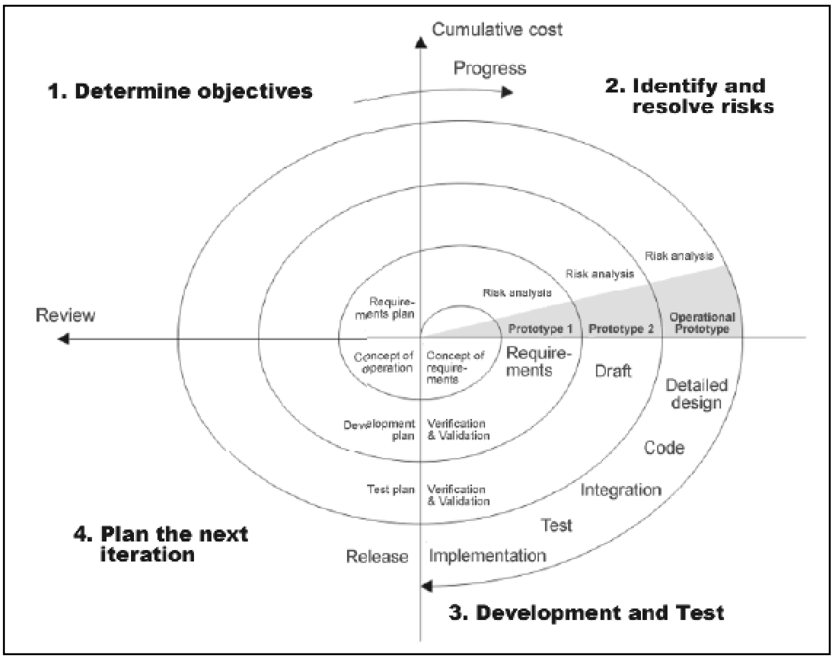

Figure 2.3: Boehm's spiral model (adapted from Ruparelia, 2010)

The spiral model represents a more cost-aware approach to system development where the consideration of the cost of risks involved in project development and successional prototype development phases act to balance out the cascade model's more traditional emphasis on establishing strict user specifications as the foundation of project development (Ruparelia, 2010). The four main sectors representing the stages of development through which the model cycles are (Boehm, 1986):

1. Determining objectives,
2. Identifying and resolving risks (including the evaluation of alternative solutions),
3. Development and testing, and
4. Planning for the next iteration.

During the risk analysis phase, potential risks are evaluated and determined to be either performance-related or development-related risks. When risks are considered to be predominantly performance-related, the process follows the spiral through another iteration until the development plan is amended such that performance-related risks are minimised. Once the risks have been determined to be predominantly development-related, the sequential phases of the traditional cascade model ensue (Ruparelia, 2010).

One clear benefit of integrating risk analysis into project development is that the risks associated with any part of project development may indicate the relative time and resources that may be required for that specific stage of project development. In this way risk management can be used to determine relative cost and to manage cost within each cycle. However the correct identification and prediction of risk, as well as the ability to respond appropriately in order to manage risk requires a flexible and experienced project development team (Ruparelia, 2010).

The review that follows the completion of each cycle represents an overview of the entire cycle leading up to that point, and includes planning for the next iteration. This approach allows for the direct involvement of stakeholders in the approval of the subsequent cycle, which serves to secure stakeholder involvement in planning as well as stakeholder commitment to the project (Ruparelia, 2010).

Iivari (1987) proposed an alteration to the spiral model in which each sector would be subdivided into two parts in order to accommodate and integrate baselines and milestones into the project development process. This hierarchical spiral model would have risk-driven main phases, but specification-driven sub-phases, thereby representing a more balanced approach to system development (Ruparelia, 2010).

Mathew *et al.* (2006) created a conceptual data warehousing prototype for water utilities in order to maximise the benefits derived from enterprise data, the data that is shared by all users within an organisation. A cyclic SDLC was proposed in order to allow for alterations to the prototype concept to be made as user needs developed. This work underlines the importance of allowing for the re-evaluation of user needs and system specifications where they cannot be readily identified or are not clearly defined at the outset.

Before deciding on an appropriate model for systems development, it is important to consider certain factors that may influence the nature of the project. These include (Balaji & Murugaiyan, 2012):

1. How stable or rigid are the user requirements?
2. Who are the prospective users of the system?
3. What is the size of the project?
4. How accessible are the project team members?

Answering these questions allows for the abilities and limitations of the design team to be taken into consideration when determining the appropriate systems design life cycle model to adopt. Where user requirements may be the subject of periodical review, the hierarchical spiral model may serve to minimise or contain risks associated with changing project specifications (Ruparelia, 2010). If the user specifications are fairly stable, then either the V-model or Royce's version of the traditional cascade model may suffice, due to their structured approach to project development based primarily on well-defined user requirements (Ruparelia, 2010).

While realistically it is not always possible to directly involve representatives of the prospective end users or stakeholders in every stage of the project development process, project development nevertheless must be done with the specific needs of the users in mind. The unique feedback regime of the V-model allows for a more structured review of the development process at each stage, while Royce's version of Benington's waterfall model provides a more flexible review structure. Both of these models are firmly based on user-specification-driven project development (Ruparelia, 2010).

While the basic cascade model can readily be adopted for any size project, the spiral model requires a more adaptive approach to project management, which could make it more challenging to implement for larger or more complex projects. The V-model was specifically developed with the capacity to accommodate large, complex projects with multiple components, making it ideal for collaborations between different project teams collaborating on a development initiative, although the frequency of the test phases along the entire system development lifecycle makes it impractical for projects that need to be developed within a short period of time (Ruparelia, 2010; Balaji & Murugaiyan, 2012).

The last factor that can have a significant impact on the nature of project development is the accessibility of the project team members throughout the development process (Balaji & Murugaiyan, 2012). If the frequency and efficacy of project meetings are inhibited by inaccessibility it may restrict and potentially compromise the review process, thereby nullifying the advantages of regular feedback events (Forsberg & Mooz, 1991). The structured feedback approach outlined by the V-model causes it to be fundamentally rigid, although the frequency of testing may require team members to be accessible for feedback, making it less practical for projects involving a widely distributed or otherwise inaccessible team (Forsberg & Mooz, 1991; Balaji & Murugaiyan, 2012).

2.6 Ontologies and the Modelling Environment

Modelling physical or abstract phenomena in a computer-based environment requires the application of qualitative and quantitative approximations in order to convert the dimensions of the phenomena being studied into subsets of Euclidean space (Requicha, 1980; Govindaraj, 1987; Wang, 2006). Requicha (1980) first distinguished between the physical, mathematical and representational stages of modelling real-world objects within a digital system. Gomes and Velho (1995) later described the process of modelling between real-world phenomena and their virtual simulation as taking place within a series of pre-defined reference frames, termed the four-universes-paradigm.

The original four universes described by Gomes and Velho (1995) were the physical universe – within which are found the phenomena that may form the subjects of the modelling exercise – the logical, or mathematical, universe – within which these phenomena are described by relational attributes or mathematically defined behaviour and relationships – the representation universe – within which the spatial aspects and symbolic representation of an object are described – and the implementation universe – whereby the concepts of the representation universe are relayed to data structures and computer language.

Fonseca *et al.* (2002a) later added a fifth universe after the physical universe, termed the cognitive universe (*Figure 2.4*). The cognitive universe serves as the go-between for objective reality and the abstraction process of observed phenomena, where the observer forms a conceptual cognitive impression of a phenomenon upon which the subsequent phases of abstraction will be based (Fonseca *et al.,* 2002a). This step acknowledges the role of observation and the subjective nature of interpretation that characterises the data creation sphere.

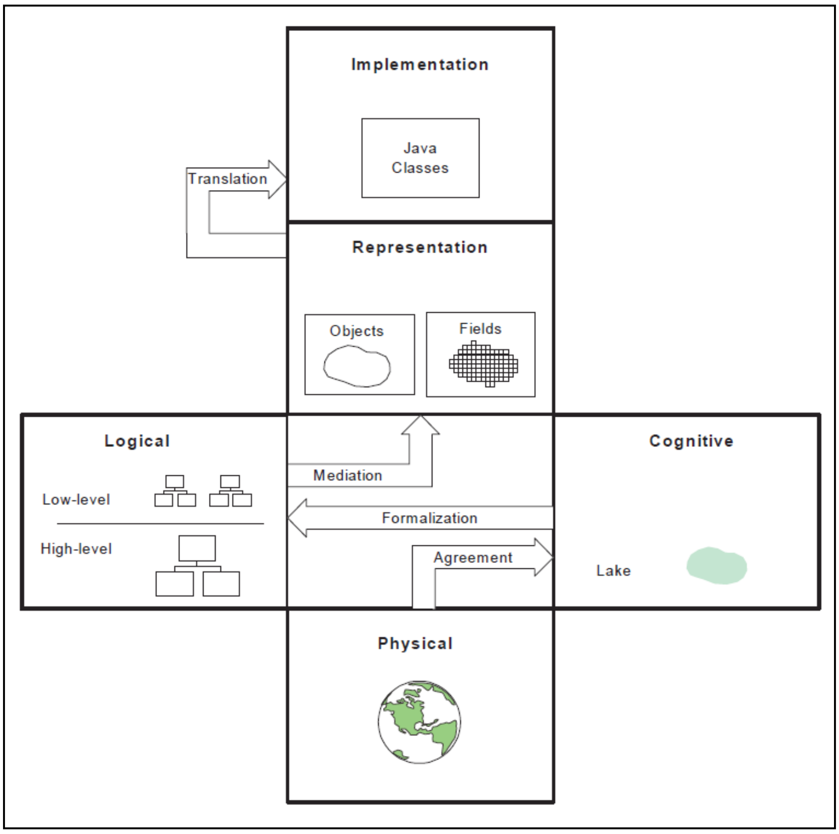

Figure 2.4: A graphic representation of the five-universe-paradigm of spatial data abstraction (Fonseca et al., 2002a)

The range of technical and measurement conventions, data storage formats and classification schemes that have been adopted by various agents according to their own needs and preferences during the process of abstraction have often inhibited the growth of data systems interoperability as a result of a high degree of heterogeneity (Guarino, 1997).

The five-universes-paradigm accepts that the physical world exists independently of its perception. Through collective agreement based on shared perception, physical phenomena can be conceptualised and classified and can so be represented virtually. The logical framework established around the conceptualisation and classification of phenomena in this way allows for the formalisation of the concepts themselves (Fonseca *et al.,* 2002a). S Scientifically speaking, once formalised, the explicitly defined logical framework is known as an ontology (Guarino & Welty, 2000).

Within the sequential five-universes-paradigm scientific ontologies therefore begin with the logical universe (Fonseca *et al.,* 2002a). As with any classification schema, ontologies can be defined according to the level of specification. High-level ontologies describe features in more general terms, while low-level ontologies infer more specialised descriptions pertaining to features and their interrelationsips. Semantic mediators form the connection between the logical and representation universes (Fonseca *et al.,* 2002a).

Within the representation universe the elements described during the logical universe are classified into distinct features for graphic representation and functional participation purposes. At this level ontologies determine the relevant practical abstractions of the physical world in terms of objects and fields. Objects are discrete and are usually defined in terms of vertices and sides – such as polygonal features, while fields are defined by an extent covered uniformly by picture elements (pixels) or grid cells (Wang, 2006).

Once the formal descriptions of the phenomena from the logical and representation levels are translated into computational elements – such as algorithms – and classes in object-oriented computer languages and data structures – such as raster and vector formats – the ontological framework is complete (Fonseca *et al.,* 2002b).

Ontologies can be chategorised based on their level of specialisation and functionality (Guarino, 1997):

- **Top-level ontologies** describe only generalised concepts and semantics that are independent from a specific problem or domain, such as defining land use types and sub-types,
- **Domain ontologies** describe the vocabulary related to a specific domain or discipline, such as water resource management or town planning,
- **Task ontologies** describe any given task or operation performed within the bounds of a relevant domain, such as network analysis or spatial interpolation, and
- **Application ontologies** describe specific tasks or operations applied within a given domain and are usually a jointly specialised version of both related ontologies, such as applying network analysis to a water reticulation system.

Ontology in the context of spatial data was defined by Gruber (1992) as “an explicit specification of a conceptualisation.” Guarino (1998) later distinguished ontologies from conceptualisations with the explanation that “an ontology is a logical theory accounting for the intended meaning of a formal vocabulary (i.e., its ontological commitment to a particular conceptualisation of the world), whereas a conceptualisation is the structure of reality as perceived and organised by an agent, independently of the vocabulary used or the actual occurrence of the specific situation.”

The importance of establishing clearly defined and complete data ontologies for the functional longevity and ready use of datasets is a logical approach, although it presents new challenges in situations where a system might require inputs from heterogeneous sources that are widely distributed in the contextual and functional domain (Sheth, 1999; Fonseca *et al.,* 2002b). For this reason establishing clearly defined standards and domain ontologies is vital for data and systems interoperability (Bittner *et al.,* 2005).

Integrating data from distributed sources generally involves managing heterogeneity in data attributes and semantics (Bittner *et al.,* 2005; Di Donato, 2010). This is due to the fact that data semantics derived from explicitly formalised conventions at top-level are infrequently of a highly standardised nature.

When data are created, both the context and the intended function of the data determine the ontology that will be used. This may be part of a natural process for the data creator with experience in producing standard data products for a known purpose through a standard process (Di Donato, 2010).

Ontologies define both the semantics of relatedness between phenomena as well as between the phenomena and their properties, at the level of observation which determines the category of ontology (Bittner *et al.,* 2005). Guarino and Welty (2000) discuss the formalisation of the ontology of properties, relating to the meta-properties of identity, unity, rigidity and dependence. These meta-properties describe the relationship between an object and its conceptualised properties (Guarino & Welty, 2000).

The meta-property of identity is carried by a property such that it uniquely identifies the object carrying that property. An example of identity would be in the meta-property of the relationship between the designated identification number of a component of a system and that component.

Unity describes the relationship between an object and its parts (Guarino & Welty, 2000). For example, a suburb and the town of which it is a part share the meta-property of unity. Rigidity relates to the changing nature of properties through time, accounting for the reality that an object may retain its identity while undergoing change. An example of this would be the water level in any particular dam. Even though the water level may rise or fall, or dry up altogether, the dam retains the same identity.

Dependence concerns the relationship between one property and another, whereby the presence of the latter is a prerequisite for the identity of the former. The concept is carried further by adding the constraint of externality, whereby the second property may not be a part or quality of the first, thereby limiting the relationship to two discrete properties (Guarino & Welty, 2000). An example of external dependence would be the sequential numbering of objects, whereby a preceding number must first be allocated before the next number may be allocated.

Câmara *et al.* (2000) discuss the implications of formalising the commonly implicit, informal design decisions that lead to the creation of spatial objects by distinguishing explicitly between the different stages, or universes of abstraction. The spatial object (SO) is defined in terms of its elements, representing the simplest component of the mathematical, or logical universe:

$$\mathrm{SO} = (\mathrm{S}, \mathrm{A}, f) \tag{3}$$

where:

$\mathrm{S} \subset \mathfrak{R}^2$ is the geometric support represented by a subset of values in the Euclidean plane,

A is a set of attribute domains $(\mathrm{A}_1, \dots, \mathrm{A}_n)$, and

$f\colon \mathrm{S} \longrightarrow \mathrm{A}_1 \times \mathrm{A}_2 \times \mathrm{A}_3 \times \dots \times \mathrm{A}_n$ is an attribute function which connects the value of an attribute domain to each location in the geometric support (Câmara *et al.,* 2000).

This notion builds on the concept of the graphical object defined by Gomes *et al.* (1996), and can be used to describe any level of geographic abstraction. Câmara *et al.* (2000) further classify spatial objects into four general classes based on the topology of the geometric support, as well as the nature of the attribute function. These classes are simple, composite, homogeneous and non-homogeneous.

Simple and composite spatial objects are defined by their topology, where a spatial object, of which the geometric support S is a single, continuous region in $\mathfrak{R}^2$, would be simple, a spatial object of which the geometric support S is a disconnected, non-continuous region in $\mathfrak{R}^2$, the spatial object would be classified as a composite. A homogeneous spatial object has a continuous attribute function $f(s) = (a_1, \dots, a_n), \forall s \in \mathrm{S}$, where a non-homogeneous spatial object does not (Câmara *et al.,* 2000).

Using this classification schema it is possible to describe a composite, non-homogeneous spatial object as one consisting of multiple distinct spatial components with an attribute function that is not constant over S. This level of spatial object classification formally defines a typical vector layer within a GIS, whereby a combination of simple homogeneous features collectively constitute a themed composite non-homogeneous object (Câmara *et al.,* 2000).

However, before phenomena can be translated into virtual concepts, some form of measurement or observation must first take place. Measured data typically fall into three categories, based on the temporal range and scale of the measurement (Gujarati & Porter, 1999). These categories are:

1. **Time-series**,

2. **Cross-sectional**, and
3. **Pooled data**.

Time-series data are collected over a period of time, usually at regularly defined intervals, and can be qualitative or quantitative (Gujarati & Porter, 1999). An example of time-series data is daily soil moisture measurements at a fixed point over a period of time, forming a series of data points spaced evenly along a temporal axis. This type of data is commonly used in change-detection exercises (Hayes & Sader, 2001; Verbesselt *et al.,* 2010; Bontemps *et al.,* 2008) or for forecasting (Hamilton, 1994).

Cross-sectional data are gathered for one or more variables at a single point in time, representing a cross-section of the phenomena being so measured. Examples of cross-sectional data include survey polls and government censuses for any given area or population group (Gujarati & Porter, 1999).

Cross-sectional data are ideal for calculating statistics based around the point in time at which the data were gathered and typically requires fewer resources to produce than time-series data, although cross-sectional data lacks the temporal depth of time-series data (Chaudhuri *et al.,* 2002)

Pooled data represent a combination of cross-sectional and time-series data (Gujarati & Porter, 1999). An example of pooled data would be annual mean temperatures for various weather stations that cover a specific region, gathered over a 40-year period. Each weather station will have a 40-year time-series of average temperature values, while each year will have a cross-section of average temperatures across the various individual weather stations.

Panel data, also known as longitudinal data, are a type of pooled data in which a fixed cross-sectional unit is surveyed at regular intervals over a period of time (Gujarati & Porter, 1999). An example of panel data is a range of meteorological measurements taken daily at the same station.

2.7 The Use of Visual Programming Languages in Spatial Modelling

Visual programming languages, such as the Workflow Designer in Autodesk Map 3D 2011 or the Model Builder application featured in ESRI's ArcGIS Desktop software package, present the opportunity for researchers not well versed in text based programming languages to build sequential models, or workflows. In ESRI's Model Builder application, for example, the models, or workflows, are built from individual geoprocessing tools located in the Toolbox application. These tools allow the user to create a workflow of processing functions, each successive operation employing as input the output of a previous operation in the workflow (*Figure 2.5*) (Dobesova, 2011).

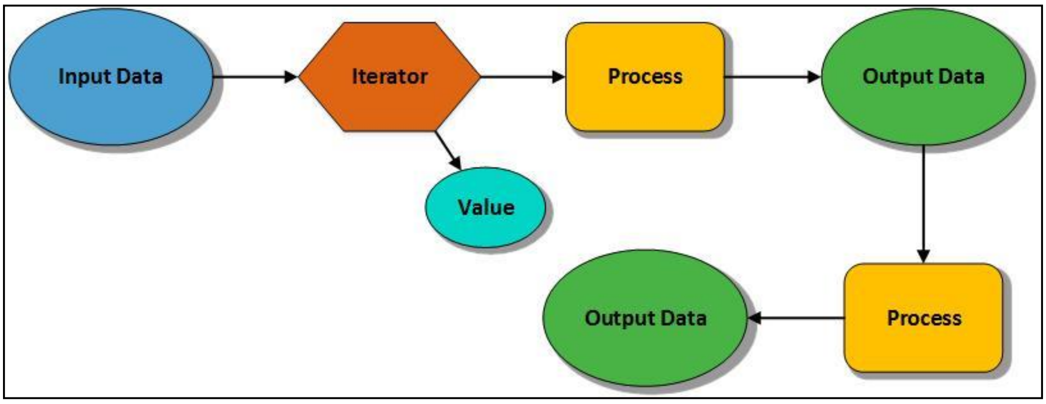

Figure 2.5: A workflow in ESRI ArcMap's Model Builder application.

The Model Builder application allows for the use of special functions within the visual modelling environment, such as the creation of custom parameters, which appear in the dialog window once the model is run as a geoprocessing tool from the toolbox. Parameters can include text variables, input files, workspaces, output locations or Boolean logic (Dobesova, 2011), and can be designated as optional or required parameters. Parameters can be formatted as a list of predefined choices in order to allow the model to operate within a set domain of possible user responses.

Additional functionality of the Model Builder includes the use of iterators, which allows the model to cycle through features, datasets or variables, as well as the use of custom Script Tools, which consist of scripts written in a text-based programming language which are then imported into the Toolbox as a Script Tool.

The use of custom Script Tools allows the user to design geoprocessing functions based on a combination of pre-existing geoprocessing tools, as well as integrating the flexibility and range of functionality of the text-based programming language, which include the handling of number arrays, creating conditions for iterative looping or alternative processing paths, opening, reading and writing files, and performing a variety of operations on different data types (Zandbergen, 2013).

Model Builder allows for separate, distinct models to be nested, or used as subroutines, within other models. Model Builder also allows for the output of one process to be used as a precondition for the initialisation of another process, thereby preventing parallel process chains from running before a required output from another process chain has been created (Dobesova, 2011).

2.8 Dasymetric Mapping and the Modifiable Areal Unit Problem

When aspatial data needs to be displayed spatially it is normally tied to some form of geo-locating data. Basing the mapping of aspatial data on enumeration units produces what is commonly referred to as the choropleth map (Eicher & Brewer, 2001).

This mapping style may serve to simplify and rapidly visualise statistical data by established enumeration zones, but in so doing it distorts the statistical properties of the aspatial data so mapped, due to the fact that the enumeration units themselves are not defined based on the spatial distribution of the aspatial data being mapped, leading to internal variation in homogeneity which is masked by the solid structures of the choropleth features (Eicher & Brewer, 2001). For example, demographic data may be displayed by country. However, the internal distribution of demographics per country would not be readily apparent through this approach.

In order to ascertain the internal distribution of said demographics it would be necessary to consult additional sources for more accurate spatial delineation, which may consist of ancillary data or expert knowledge (Eicher & Brewer, 2001). Such ancillary data may then provide a basis for spatially downscaling the original dataset in order to produce a more realistic spatial distribution or to re-aggregate data so that datasets with different levels of spatial aggregation may be compared or jointly analysed.

The process of converting a dataset from one enumeration unit to another is known as areal interpolation. Various methods exist by which to perform areal interpolation, and some aspects of the methodology of areal interpolation may be readily transferable to the practice of dasymetric mapping (Eicher & Brewer, 2001; Bloom *et al.,* 1996; Fisher & Langford, 1995).

Dasymetric mapping involves the display of statistical data by significant areal units (Eicher & Brewer, 2001). Areal units for dasymetric mapping are generally chosen for their statistical homogeneity, such that boundaries between objects reflect changes in the spatial distribution of the mapped data (Eicher & Brewer, 2001).

The point of departure between areal interpolation and dasymetric mapping lies in the ultimate re-aggregation to a new enumeration unit which characterises areal interpolation methodologies (Eicher & Brewer, 2001). It is therefore possible to incorporate certain approaches used in areal interpolation when undertaking dasymetric mapping. The benefit of the dasymetric approach is in preserving the statistical integrity of the original data by rendering a less aggregated spatial statistical surface (Eicher & Brewer, 2001).

The main issue that arises from choropleth mapping, which is addressed through application of dasymetric methods, is the modifiable areal unit problem (MAUP) (Openshaw & Taylor, 1979; Dark & Bram, 2007). The MAUP can be visualised by examining the changing statistical properties of data at different levels of aggregation (*Figure 2.6*).

a)

6	4	9	8
5	2	7	6
7	8	1	5
1	2	4	3

$\bar{x} = 4.88$
$\sigma^2 = 6.65$

b)

5	8.5
3.5	6.5
7.5	3
1.5	3.5

$\bar{x} = 4.88$
$\sigma^2 = 5.91$

c)

4.25	7.5
4.5	3.25

$\bar{x} = 4.88$
$\sigma^2 = 3.35$

d)

5.5	3	8	7
4	5	2.5	4

$\bar{x} = 4.88$
$\sigma^2 = 3.63$

e)

4.75	4	5.25	5.5

$\bar{x} = 4.88$
$\sigma^2 = 0.44$

f)

6.33	8
4.11	4.67

$\bar{x} = 5.78$
$\sigma^2 = 3.08$

Figure 2.6: Example of the primary effects of the modifiable areal unit problem on the statistical properties of a dataset; a – c demonstrate the effects of aggregation, where the mean remains the same but the variance decreases with increasing levels of aggregation, and d – f demonstrate the effects of alternate aggregation units. In d and f the mean remains the same, but the variance chances substantially, while in f both the mean and the variance are affected.

Openshaw and Taylor (1979) highlighted two primary issues associated with the MAUP – the scale effect and the zonation effect. The scale effect involves changes in the statistical attributes of a dataset as a direct result of the number of enumeration units that an area is subdivided into (Openshaw & Taylor, 1979). The zonation effect involves changes in the statistical attributes of a dataset as a result of the aggregation approach (Openshaw & Taylor, 1979).

As a result, even when the number of enumeration zones (represented by the number of cells in each table in the example given in *Figure 2.6*) are kept constant, the mean and variance of statistical data may still be affected (Openshaw & Taylor, 1979). In this way the spatial and statistical distributions of a dataset become distorted by the chosen method of aggregation.

Dasymetric mapping, through the use of appropriate ancillary data, allows for the creation of statistically homogeneous areal units separated by boundaries corresponding to changes in the distribution of the mapped variable (Eicher & Brewer, 2001). MacEachren (1994) implied that, because of the level of disaggregation in dasymetric mapping, it falls somewhere between isopleth and choropleth mapping in terms of statistical surface smoothness. As a result dasymmetry has been selected as a means to spatially delineate activities related to water consumption.

The sections in this chapter have explored various topics related to the estimation and modelling of water use within a spatial context - from conceptual paradigms to the general tools and methodologies usually required to perform such analysis. While it is far from exhaustive, it should at the very least serve to illustrate the complex and indeed challenging nature of such an undertaking, and the wide variety of options from which to choose regarding methodology and approach. Given the diversified nature of the problems at hand it is the purpose of this study to highlight one possible path among many, and to discuss its shortcomings and advantages.

Chapter 3: Study Area

3.1 An Overview of the Berg River Catchment: Topography, Geology, Hydrology and Climate

South Africa's Western Cape is a region estimated to be approaching physical water scarcity in the near future as a result of climate change (UNESCO, 2012). The Berg River catchment is the largest catchment in the Western Cape Province, covering nearly 9 000 km^2 (DWAF, 2007a). The Berg River's source is located in the Drakenstein and Franschhoek Mountains south of Franshhoek, from which it runs north and west in a westward trending arc, eventually discharging into the Atlantic Ocean in St Helena Bay near Velddrif (DWAF, 2007a) (*Figure 3.1*).

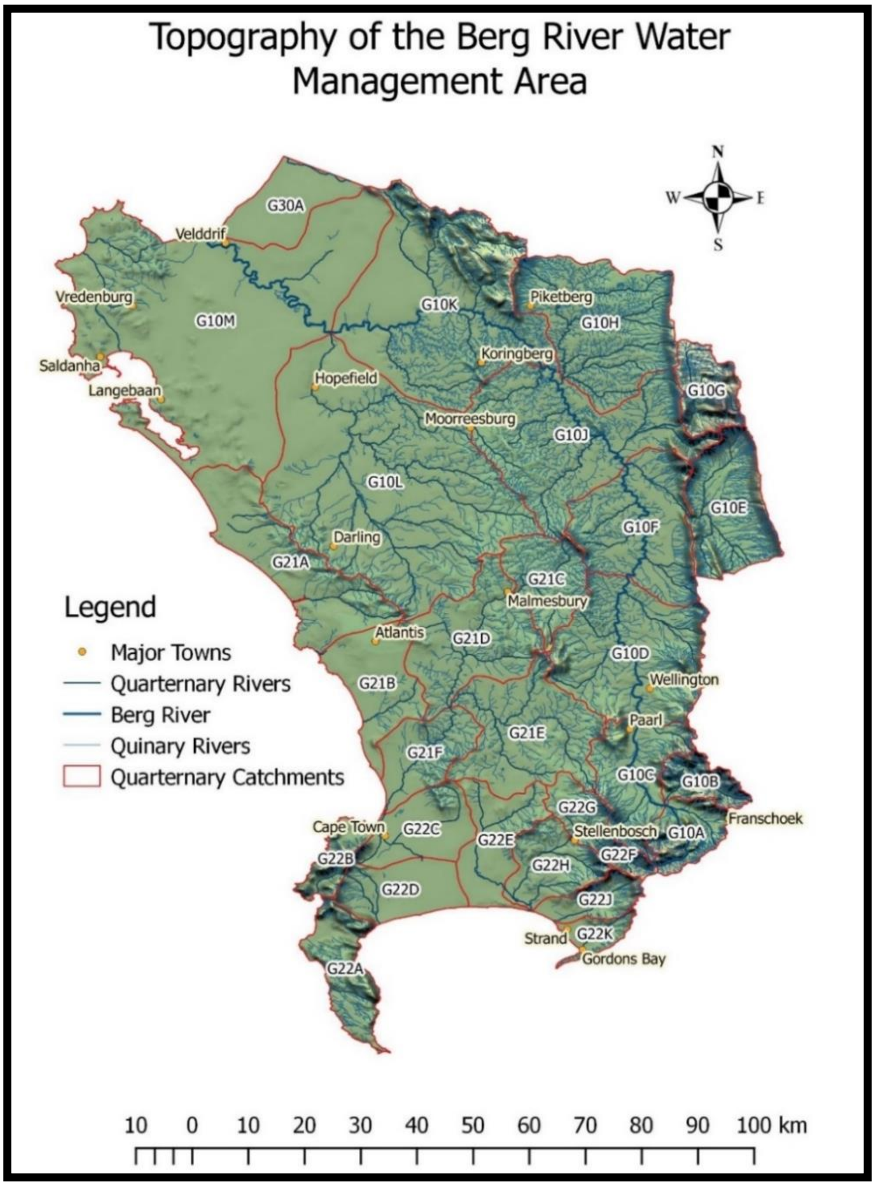

Figure 3.1: Quaternary Catchments of the Berg River (Sources: DEA&DP, DoA Elsenburg, DED&T)

Based on the geographic and topographic characteristics this catchment can be divided into three distinct areas; the mountainous source area south of Paarl, the river valley area east of Koringberg to just south of Paarl, and the coastal plain area west of Moorreesburg and Koringberg (DWAF, 2007a). In the western portion the main population centres are Saldanha, Vredenburg and Hopefield, while the main population centres in the river valley section are Piketberg, Porterville, Malmesbury, Paarl and Wellington (DWAF, 2007a).

The Berg River Catchment itself is divided into 12 quaternary catchments, varying in size from G10A and G10B near the headwaters of the river, covering 170 km^2 and 125 km^2 respectively, to G10L and G10M in the drier western parts of the river, covering areas of 1 750 km^2 and 2 000 km^2 respectively (DWAF, 2007a). After the confluence with the Franschhoek River, the Berg River drops steeply and the Klein Berg, Vier-en-Twintig and Krom Rivers flow into the Berg River from the Piketberg Mountains, after which the Berg River is joined by the Sout River, which flows north-eastwards from the Paardeberg (DEA&DP, 2012).

There are 19 major tributaries of the Berg River, including the Franshhoek, Wemmershoek, Dwars, Hugos, Krom, Kompagnies, Klein Berg, Twenty-Four (Vier-en-Twintig), Sandspruit, Matjies and Sout Rivers (DWAF, 2007a). The natural runoff of the Berg River catchment has been estimated to be 931 Mm^3/a (DEA&DP, 2012). A large proportion of the total volume originates from the upper reaches of the Berg River, where the Franschhoek, Wemmershoek, Dwars, Klein Berg, Kuilders and Twenty-Four rivers contribute year-round runoff into the Berg River, albeit with substantial reductions in flow during the summer months (DWAF, 1992). Apart from these perennial systems, all other tributaries cease to flow during summer months (Fourie & Görgens, 1977).

The Berg River Catchment is characterised by a low drainage density in the western parts of the catchment, which is underlain mostly by sandy recent fluvial deposits (DWAF, 2007a). However, the central and eastern sections of the catchment are characterised by significantly high drainage densities (*Figure 3.2*). Here the catchment is underlain by weathered and fractured rocks of the Malmesbury Group (predominantly shales) and Table Mountain Group (predominantly quartzitic sandstones) (DWAF, 2007a).

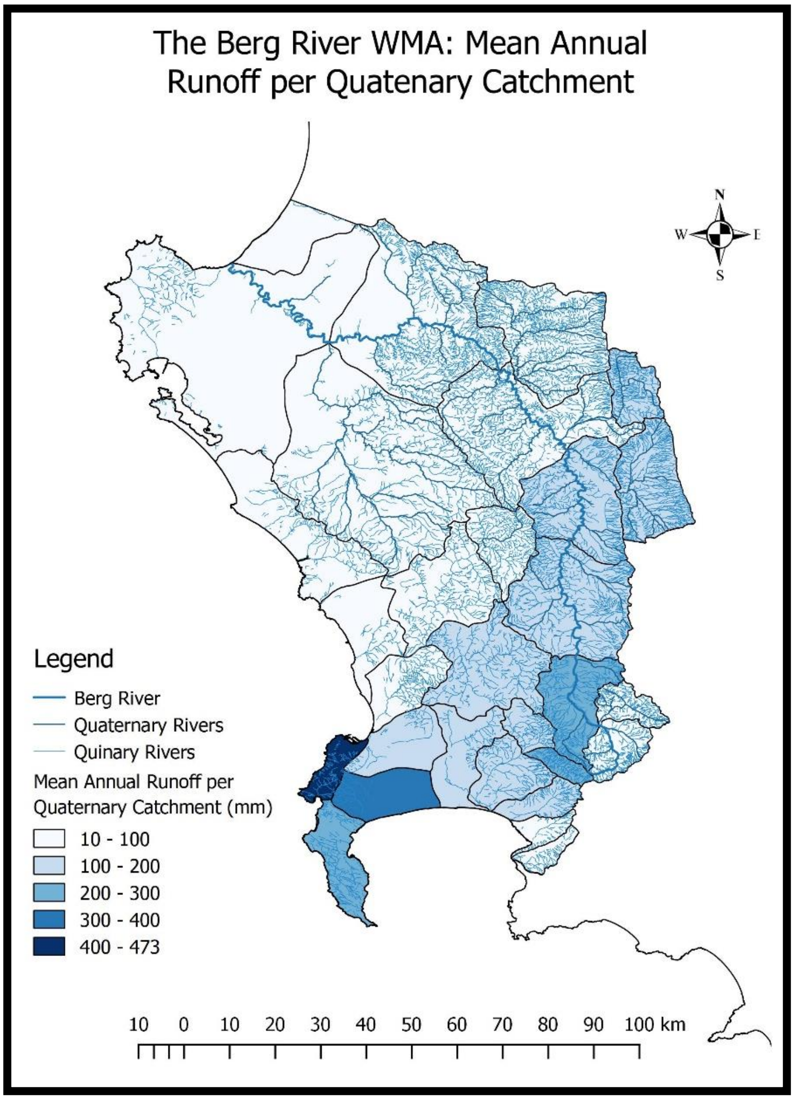

Figure 3.2: Mean annual runoff in millimetres per quaternary catchment of the Berg River Water Management Area (DWAF 1992).

The Berg River catchment contains five major aquifer systems: the Table Mountain Group Aquifer, the Malmesbury Group Aquifer, the Cape Granite Suite Aquifer, the Klipheuwel Group Aquifer and the Primary Aquifers. Groundwater is characterised by high salinity towards the coast, with higher quality groundwater found towards the upper reaches of the Berg River catchment (DEA&DP, 2012).

Roughly 13% of the Berg River Catchment contains a high density of alien vegetation, mostly around Langebaan and Hopefield (DWAF, 2007a). It is estimated that, in 2007 riparian invasion reduced flow by 1.3 million m^3 (DWAF, 2007a). If cleared, it was estimated that the yield at Misverstand Weir could be increased by approximately 1.0 million m^3/a while, if left uninhibited, an additional loss in yield of roughly 0.8 million m^3/a could potentially result (DWAF, 2007a).

The climate in the Berg River Catchment can be described as Mediterranean, with rainfall predominantly occurring in winter, while the summers are hot and dry (DWAF, 2007a). Rainfall is cyclonic in nature, lasting for a few days at a time, separated by days of clear weather (DWAF, 2007a). The main source of precipitation comes from frontal systems that periodically pass over the Western Cape, enhanced by orographic lift due to air flowing over the mountainous terrain. As a result of the orographic influence, the annual rainfall across the catchment varies spatially, with markedly higher rates of precipitation experienced in the south-eastern mountainous region of the catchment compared to that of the north-western region (DWAF, 2007a).

3.2 The Berg Water Management Area: Population, Industry and Agriculture

The human population within the Berg River Water Management Area (WMA) is estimated to be over 5.4 million (*Table 3.1*) (StatsSA, 2012), with 3.86 million residing in the City of Cape Town (*Figure 3.3*) (CoCT, 2014), which draws most of its water from the Berg River.

Table 3.1: Populations of local municipalities in the Berg WMA (Stats SA (2012), CoCT (2014))

Local Municipality	**Population (Census 2011)**
Bergrivier Local Municipality	61 898
City of Cape Town Metropolitan Municipality	3 860 025
Drakenstein Local Municipality	251 261
Saldanha Bay Local Municipality	99 190
Stellenbosch Local Municipality	155 729
Swartland Local Municipality	113 764
Witzenberg Local Municipality	52 152
Total	**4 639 347**

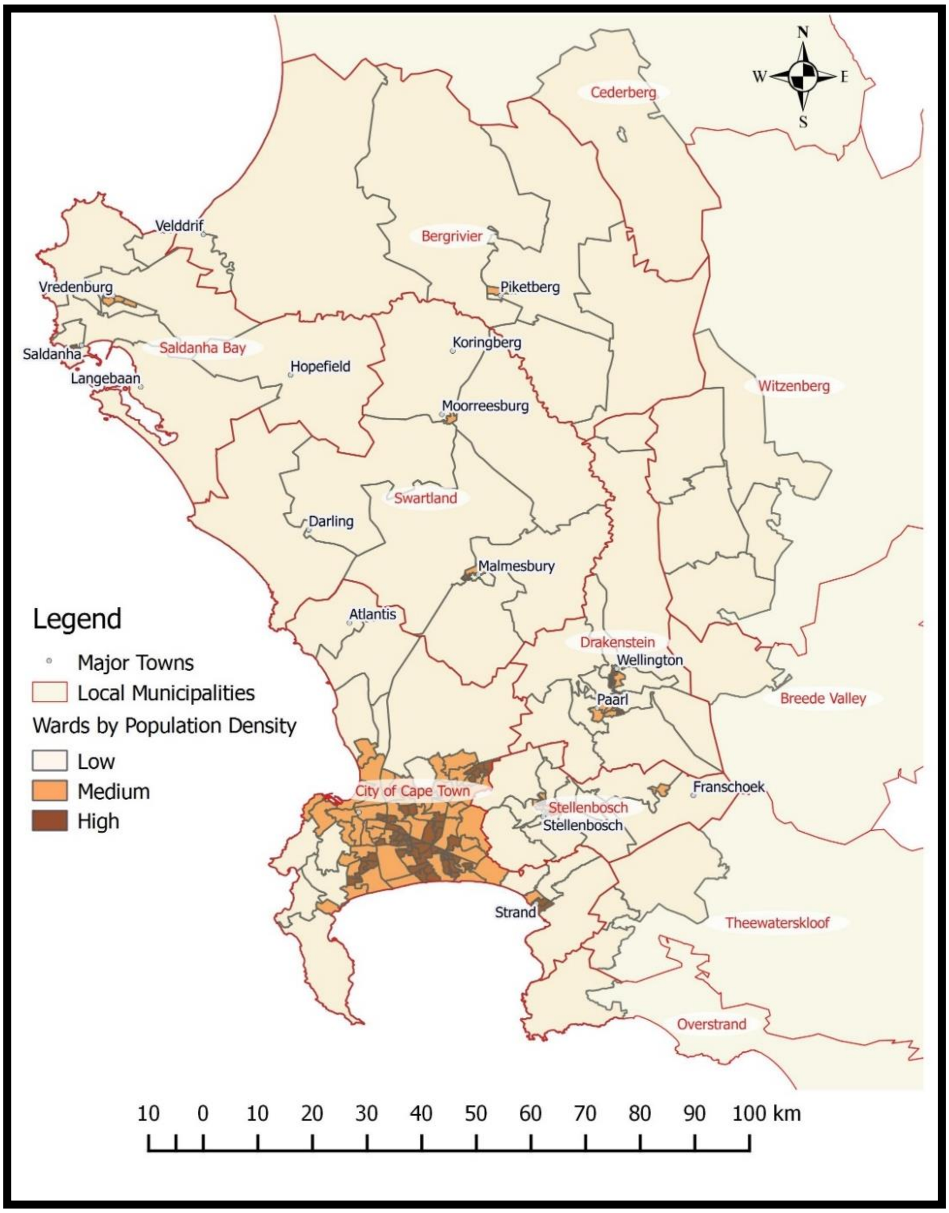

Figure 3.3: Relative population densities of wards within the Berg Water Management Area (Source: DEA&DP, StatsSA (2012)).

A study done by the Cape Action Plan for People and the Environment (CAPE) estimated that 24% of the Berg River Catchment consists of urbanised areas, while another 60% is developed for agricultural purposes (DWAF, 2007a) (*Figure 3.4*). Land use within the Berg River Catchment includes livestock production, forestry, fruit farming, wheat farming, commercial industry, residential areas and nature reserves (DWAF, 2007a).

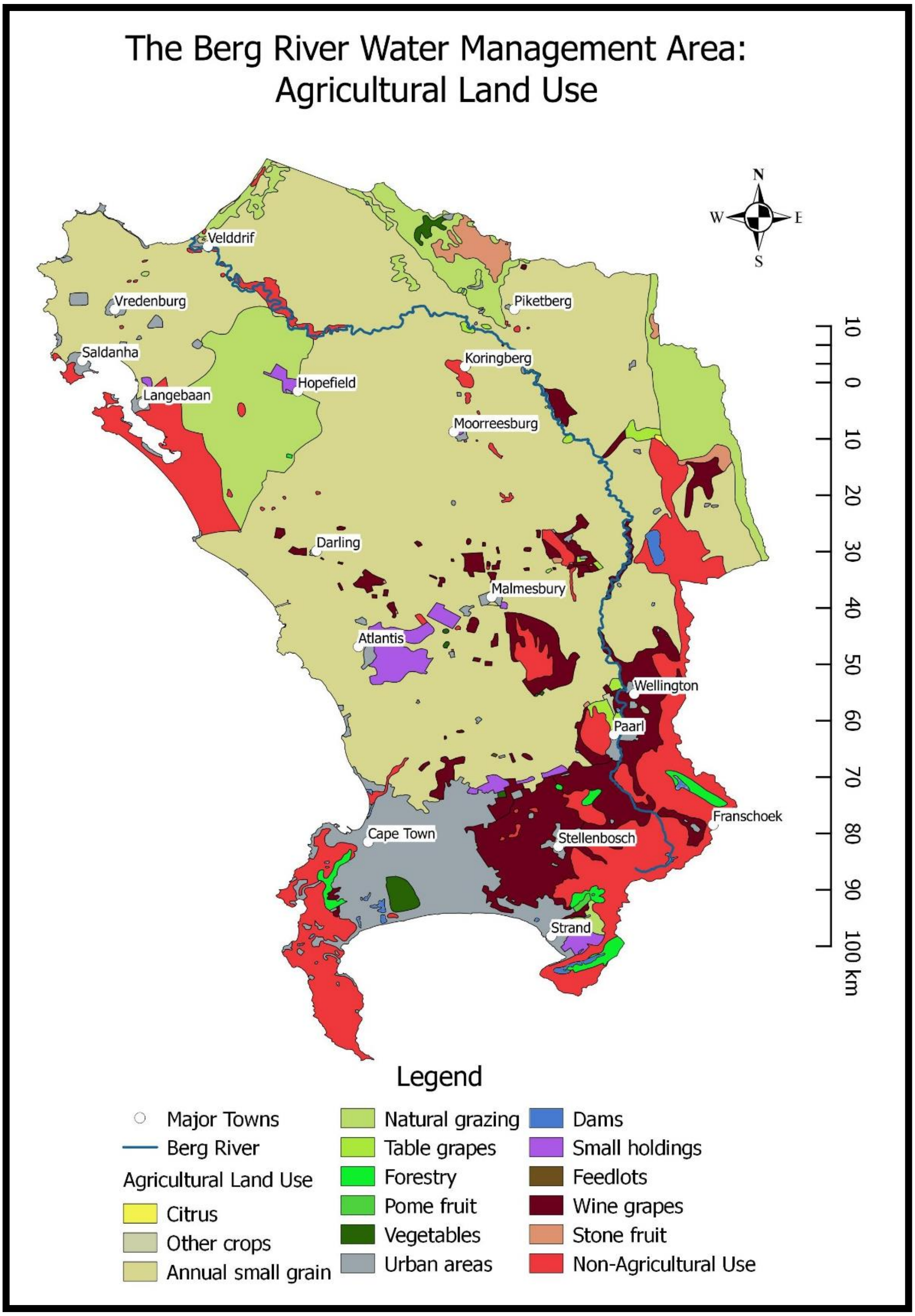

Figure 3.4: Agricultural land use in the Berg Water Management Area (Source: DEA&DP, DoA Elsenburg).

Table 3.2 contains a summary of cultivated agricultural land use types and the estimated area under cultivation for each management practice (DoA Elsenberg, 2011). By far the largest agricultural land user is rain fed planted pasture, with viticulture the largest irrigated agricultural land user. Centre pivot irrigation and shade-netting practices represent the smallest share of agricultural land use. A substantial proportion of agricultural land is used for strip farming, where alternating rows of crops are planted in strips in order to avoid soil erosion (Licht & Al-Kaisi, 2005).

Table 3.2: Total area of cultivated field types within the former Berg River WMA (Source: DoA Elsenburg, 2011)

Cultivated Field Management Practices	Total Area (Hectares)
Annual Crop Cultivation/Planted Pastures Rotation	492 047.800
Viticulture	81 623.680
Old Fields	23 745.780
Centre Pivot Irrigation	7 222.271
Shade Netting	138.709
Small Holdings	1 045.214
Strip Field Cultivation	18 785.440
Total	**624 608.890**

Agricultural production is mainly divided into irrigated (grapes, fruit and vegetables) and non-irrigated (natural grazing and small grain) farming practices. Table grapes, fruit and wine are usually produced for export, while vegetables are produced for local consumption (DWA, 2011). In 2011 it was estimated that around 8% of the overall water requirements for the Berg Water Management Area was being met through groundwater abstraction, mostly for irrigation in the Cape Flats area and in the upper reaches of the Berg River, and for urban use in Atlantis (DWA, 2011).

There are five major dams along the Berg River, supplying water to most of the municipal and agricultural demands (DED&T, 2015a). These dams form part of a water supply infrastructure known as the Western Cape Water Supply System (WCWSS), which allows for the transfer of water between reservoirs. *Table 3.3* summarises the capacity, maximum yield, or maximum amount that may be abstracted, and historical firm yield, or the maximum yield that could reliably be taken from the source during the most severe drought on record. This process increases the total system capacity by allowing full dams to release water into empty dams downstream. The largest dam that forms part of the WCWSS, Theewaterskloof (*Figure 3.5*), is situated in the catchment of the Breede River, which borders on the Berg River

Catchment, and which supplies water to the Berg River through an inter-basin transfer (DED&T, 2015a).

Table 3.3: Dams in the Western Cape Water Supply System. (Adapted from DWA, 2012)

Dam	Capacity (million m^3)	Yield (million m^3/a)	Historical Firm Yield (million m^3/a)
Theewaterskloof	432	219	193
Voëlvlei	158	105	96
Wemmershoek	58	54	48
Upper Steenbras	30	40	38
Lower Steenbras	34	-	
Berg River Dam	127	80	99
Palmiet	-	23	23
Compensation Releases	-	38	38
Additional yield from integration	-	11	13
Total:	839	570	548

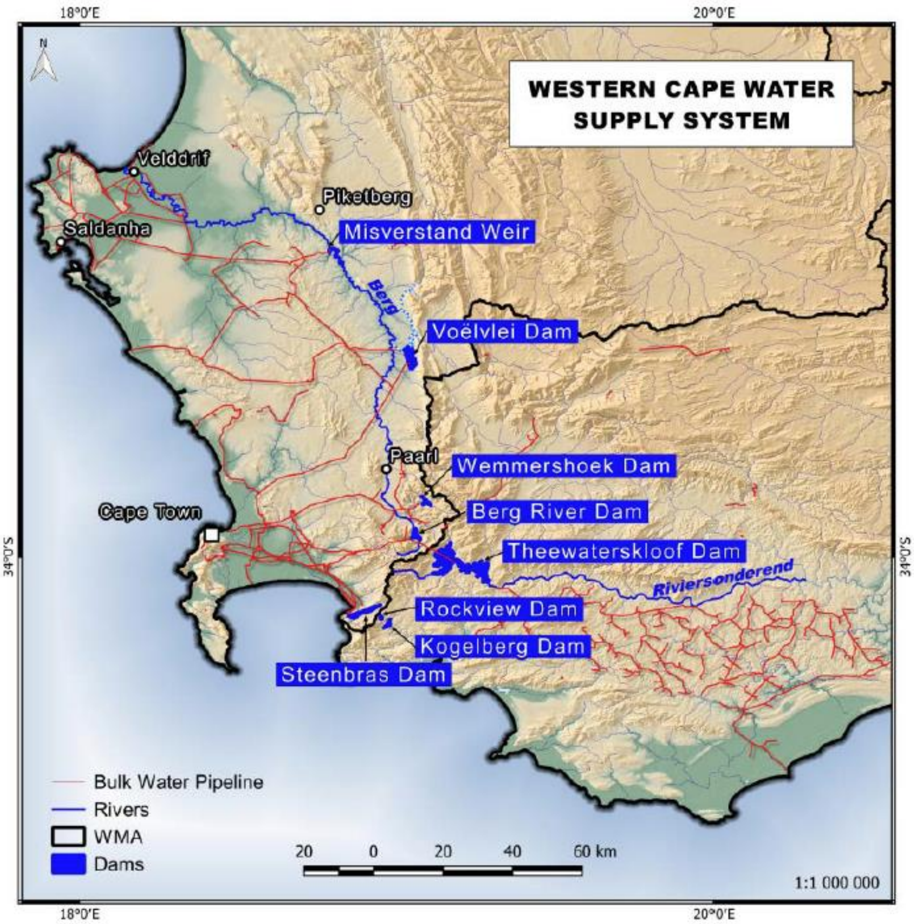

Figure 3.5: Western Cape Water Supply System (Source https://www.dwa.gov.za/Projects/RS_WC_WSS/sa.aspx, accessed 2016/12/27).

The WCWSS supplies the economic hub of the Western Cape, including the City of Cape Town, urban water users and irrigators along the Berg, Eerste, Lourens, Steenbras and Palmiet Rivers, domestic and industrial users along the West Coast, and irrigators and urban users in the Riviersonderend Catchment in the neighbouring Breede Water Management Area (DWA, 2012). Along with the Tweewaterskloof Dam, the Voëlvlei, Wemmershoek, Upper Steenbras, Lower Steenbras, Palmiet and Berg River Dams *(Table 3.3)* provide a total system yield of 570 million m^3/a with a 98% assurance of supply – known as the firm yield - which means that supply is estimated to fail once in 50 years (DED&T, 2015b).

Not all runoff can be fully utilised for socio-economic activities, as a certain amount of water must remain within the river system in order to sustain the associated ecosystems. This unconsumed water is known as the reserve flow. Water is often released from one dam to another in order to optimise storage potential. These are known as compensation releases.

The WCWSS supplies water to residential and industrial users through local municipalities, while water is supplied to agricultural users through Water User Associations and Irrigation Boards. *Table 3.4* shows allocations from the WCWSS as well as recent use derived from municipal records and crop irrigation models. The City of Cape Town is the largest domestic and industrial water user. The West Coast District Municipality and Stellenbosch Local Municipality both receive water from the WCWSS (DWAF, 2004).

Table 3.4: Current urban water allocation and recent urban water use of the Western Cape Water Supply System (Adapted from DED&T, 2015a).

User	Allocation (m^3/a)	2012/2013 Use (m^3/a)	2013/2014 Use (m^3/a)
City of Cape Town	385.90	312.92	306.77
West Coast District Municipality	21.64	25.29	26.86
Stellenbosch Local Municipality	3.00	3.00	4.01
Agriculture	173.60	169.00	170.00
Total (Excluding City of Cape Town):	198.24	197.29	200.88
Total:	584.14	510.21	507.65

Water for agricultural use is supplied from the WCWSS through various Water Users Associations (WUA) and Irrigation Boards (IB). *Table 3.5* shows the specific allocations and requirements from the main IB's and WUA's. Allocation of water for agriculture within the

Berg River Catchment has been limited to around 197 Mm^3/a, while the irrigation requirement from the WCWSS has been estimated to regularly exceed that amount by up to 20 million m^3/a (DWS, 2015a).

Table 3.5: Agricultural Water Allocations per IB/WUA. (Adapted from DWS, 2015a)

Water User Association /Irrigation Board	Capped Allocation (Mm^3/a)	Registered Volumes (Mm^3/a)	WCWSS Allocation (Mm^3/a)	WCWSS Requirement (Mm^3/a)
Lower Berg IB	18.1	21.27	31.27	41.39
Upper Berg IB	58.6	74.2	73.66	59.35
Zonderend IB	31.5	35.92	36.11	41.46
Vyeboom IB	14.7	14.18	29.51	29.51
Banhoek IB	1.8	1.8	1.8	1.8
Users on Dasbos outlet	-	0.2	0.18	0.18
Wynland WUA: Stellenbosch District	12.0	12.04	11.01	11.91
Wynland WUA: Helderberg District	12.1	12.11	11.0	11.0
Wynland WUA: Eerste River District	4.3	1.65	3.15	3.15
Compensation Releases	16.5	-	-	16.5
Overberg Water	4.0	-	-	-
Total	**173.6**	**173.37**	**197.69**	**216.25**

The City of Cape Town has implemented various strategies to reduce domestic water consumption and minimise water losses, causing overall consumption from the WCWSS to drop for the past three years. In response to over-allocation causing strain on the system, water allocation for agricultural use has been capped, such that no further increases in water use by the sector is permitted (DWS, 2014).

Chapter 4: Data

Water resource management concerns the monitoring and assessment of a wide variety of factors, including infrastructure, the quality and reliability of supply, the nature and location of demand and the policy environment that directs planning and decision making (Grigg, 1996; New, 2002; Ragab & Prudhomme, 2002). Datasets are generated and managed by entities operating within the sphere of water resource management based on their roles and responsibilities. These entities range from government organisations to private firms, each with their own data handling procedures and standards. According to the National Water Act (RSA, Act 36 of 1998):

"Monitoring, recording, assessing and disseminating information on water resources is critically important for achieving the objects of the Act. Part 1 of this Chapter places a duty on the Minister, as soon as it is practicable to do so, to establish national monitoring systems. The purpose of the systems will be to facilitate the continued and co-ordinated monitoring of various aspects of water resources by collecting relevant information and data, through established procedures and mechanisms, from a variety of sources including organs of state, water management institutions and water users."

While this in theory represents a sound approach, as a result much of the data required to build a more complete picture of water use is often scattered between various organisations, in a variety of configurations and levels of completeness, leading to accessibility and compatibility issues, as well as the potential for redundancy in record keeping (Ziervogel *et al.,* 2010; McKenzie *et al.,* 2012; City of Cape Town, 2014). Owing to this, it has been extremely challenging for the student to acquire knowledge of data availability, and to acquire the data itself, during this study.

Irrigation demand is normally estimated through soil water and energy balance calculations at various levels (Allen *et al.,* 1998; Muttiah & Arnold, 2005; Fortes *et al.,* 2005). Direct water abstraction figures are registered by users and are stored separately from other records of supply (DWAF, 2004). These records reflect user estimates of abstracted volumes of water, and may differ from measured values.

Table 4.1 summarises the primary datasets that were used in this study. The grid-based land cover dataset derived from Landsat imagery provided a basis for the determinant layers as discussed in the methodology chapter. The land use dataset was reclassified in order to distinguish between residential, commercial and other land uses. The reclassification process is outlined in section *5.2.1*.

Table 4.1: Summary of datasets used in this study.

Data	Source	Notes
2013-2014 South African National Land-Cover/Use Dataset	SANBI (copyright GeoTerraImage, 2015)	Grid of 72 classes, 30m x 30m resolution, based on Landsat 8 imagery.
Municipal Water Services Records	Various local municipalities (WorleyParsons)	Residential and commercial billed, metered water consumption figures, total system input volume per town.
Flyover 2013 Cultivated Fields	Wester Cape Department of Agriculture (2013)	Polygon shapefile of cultivated fields, including crop and irrigation types, digitised form Spot 5 imagery of 2011 and 2012 and aerial photographs of 2010.
Reference Crop Evapotranspiration by the Penman-Monteith Method	2007 Agrohydrological Atlas - WRC	Continuous surface raster file of interpolated monthly reference crop evapotranspiration rates with a 1'x1' or ~1.7 x1.7 km resolution.
Census 2011 Urban Demographics	StatsSA (2012)	Municipal boundaries shapefiles and population data averaged over the period between 1979 and 2013.
WFDEI Mean Monthly Temperature Dataset	www.eu-watch.org	Monthly mean temperature data in a 0.5 x 0.5 degree grid averaged over the period between 1979 and 2013.
WFDEI Effective Rainfall Dataset	www.eu-watch.org	Monthly effective rainfall data in a 0.5 x 0.5 degree, or ~55.5 x 55.5 km grid.
Crop Coefficients	Allen *et al.* (1998), Green and Moreshet (1979), Van Zyl & Fourie (1988), Taylor & Gush (2014)	Berries, Citrus fruits, Winter Grains, Grapes, Herbs/Essential oils, Vegetables, Nuts, Oil seeds, Pepo, Planted Pastures, Pome Fruit, Prickly Pears, Stone Fruit, Sub-Tropical Fruit, Other Tree Fruit.

The municipal Water Services Audit Reports data represent a combination of water losses, or unaccounted-for water (UAW), and authorised consumption, together making up the system input volume, or piped-in water (*Table 4.2*). Authorised consumption can further be subdivided into billed metered consumption, billed unmetered consumption, unbilled metered consumption and unbilled unmetered consumption. Billed metered water is typically divided into commercial, agricultural, residential and other consumption, including municipal water by the various water services authorities (WSA) (McKenzie *et al.,* 2012).

Table 4.2: Breakdown of water consumption and losses.

<table>
<tr><td rowspan="6">System Input Volume:
• Total water treated, measured at treatment outlet
• Total water pumped directly from boreholes into reticulation system
• Total water purchased from bulk water services provider</td><td rowspan="4">Authorised Consumption:
Total water used for legitimate purposes</td><td>Billed Metered Consumption</td><td rowspan="2">Revenue Water</td></tr>
<tr><td>Billed Unmetered Consumption</td></tr>
<tr><td>Unbilled Metered</td><td rowspan="4">Non-Revenue Water</td></tr>
<tr><td>Unbilled Unmetered</td></tr>
<tr><td rowspan="2">Total Losses:
Total water not used for legitimate purposes (Unaccounted-for Water, UAW/UFW)</td><td>Apparent Losses:
Illegal connections, administrative errors, etc.</td></tr>
<tr><td>Real Losses:
Leakages, overflows from reservoirs, etc.)</td></tr>
</table>

Ideally, household-level water use data would have allowed for a more disaggregated overview of the spatial water demand distribution than town-level aggregated records, had such data been available. However, only aggregated records of urban water use were accessible for this project. Additionally, coupling land use with water demand for commercial enterprises such that more water-intensive commercial activities may more readily be spatially distinguished from less water-intensive commercial activities remains a challenge when water use records do not include information on the nature and volume of each commercial user’s water demand.

Spatially modelling urban water demand based on the available data therefore required the classification and delineation of specific zones in order to assign blanket water requirement rates based on the reported total usage of each town. Main Places (enumeration units subdividing local municipalities, separating urban centres from rural areas) were used as a means of specifying zonal boundaries for land use-water requirements joining.

Agriculture uses water for a variety of activities. Water is lost through percolation, evaporation from soil and water bodies, and through evapotranspiration during plant growth. Activities such as flushing accumulated salts from soils to improve soil quality, as well as using open canals for transferring irrigation water increases the overall demand within the sector (Burt *et al.,* 1997).

In this study, however, focus was placed only on the water lost through evapotranspiration processes, taking into account rainwater that entered the soil and was thereby made available to the plant. As a result factors such as the water holding capacity, rate of deep percolation (water flowing down through soil horizons beyond the reach of plant roots) and rate of infiltration were not considered.

A polygon feature class dataset containing field boundaries surveyed by remote sensing (Western Cape Department of Agriculture, 2013) was used as a basis for the calculation of irrigation demand. The datas*et al*so provided important attribute data pertaining to each field's irrigation regime and crop types. From this data dryland fields could be identified and removed as their consumption of green water would not be considered in this study.

Monthly cumulative effective rainfall over the period between 1979 and 2013 was obtained in the form of a grid of 0.5 x 0.5 degrees (www.eu-watch.org). Downscaled precipitation data was available but was not used due to limitations in the ability of downscaling methodology to accurately portray daily rainfall variability (Wilby & Wigley, 1997). Monthly reference evapotranspiration, calculated by the Penman-Monteith method, was taken from the WRC's 2007 Agrohydrological Atlas (Schultze *et al*., 2007). This data was used to extract monthly effective rainfall and to calculate monthly reference crop evapotranspiration rates per field.

The polygonal fields were rasterised into 30m x 30m grid cells congruent with the raster land use dataset in order to allow for integration with land use. Due to the nature of rasterisation (*Figure 4.1*) some losses in area resulted. Smaller fields and fields that were in close proximity or with complex borders were affected most.

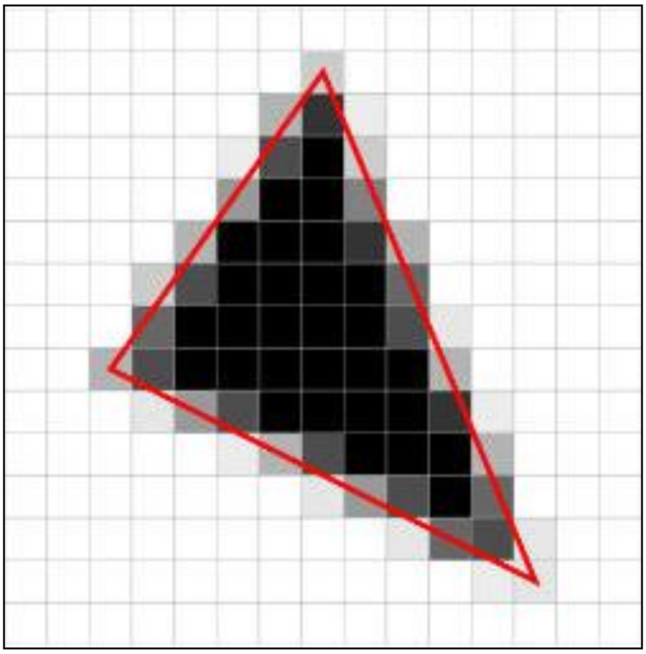

Figure 4.1: Rasterisation of a vector polygon (adapted from http:www.computerhope.com).

In order to investigate the potential range of future irrigation water requirements, mean daily temperature and effective rainfall data from several General Circulation Models (GCMs) were investigated. Observed data from 1979 to 2014 was analysed and compared with data from eleven of the twenty climate models that formed part of the fifth phase of the Climate Model Intercomparison Project (CMIP5) (Li, 2014; Ji *et al.,* 2014; Chylek *et al.,* 2011; Voldoire *et al.,* 2013; Bao *et al.,* 2013; Watanabe *et al.,* 2010; Watanabe *et al.,* 2011; Yukimoto *et al.,* 2012; Taylor *et al.,* 2012) over the same period to identify models representing drier, wetter and more temperate trends over the study area.

The following models were evaluated: the Beijing Climate Center Climate System Model (BCC-CSM1-1), the Beijing Normal University Earth System Model (BNU-ESM), the second generation Canadian Earth System Model (CanESM2), the Centre National de Recherches Météorologiques' GCM (CNRM-CM5), the Flexible Global Ocean-Atmosphere-Land System model, Spectral Version 2 (FGOALS-s2), the National Oceanic and Atmospheric

Administration Geophysical Fluid Dynamics Laboratory's Earth Systems Models with General and Modular Ocean Models (GFDL-ESM2G, GFDL-ESM2M), the Model for Interdisciplinary Research on Climate and associate Earth System Models (MIROC5, MIROC-ESM, MIROC-ESM-CHEM), as well as the Japanese Meteorological Research Institute's Coupled Global Climate Model (MRI-CGCM3) (*Figure 4.2*). No particular method was followed in selecting these models.

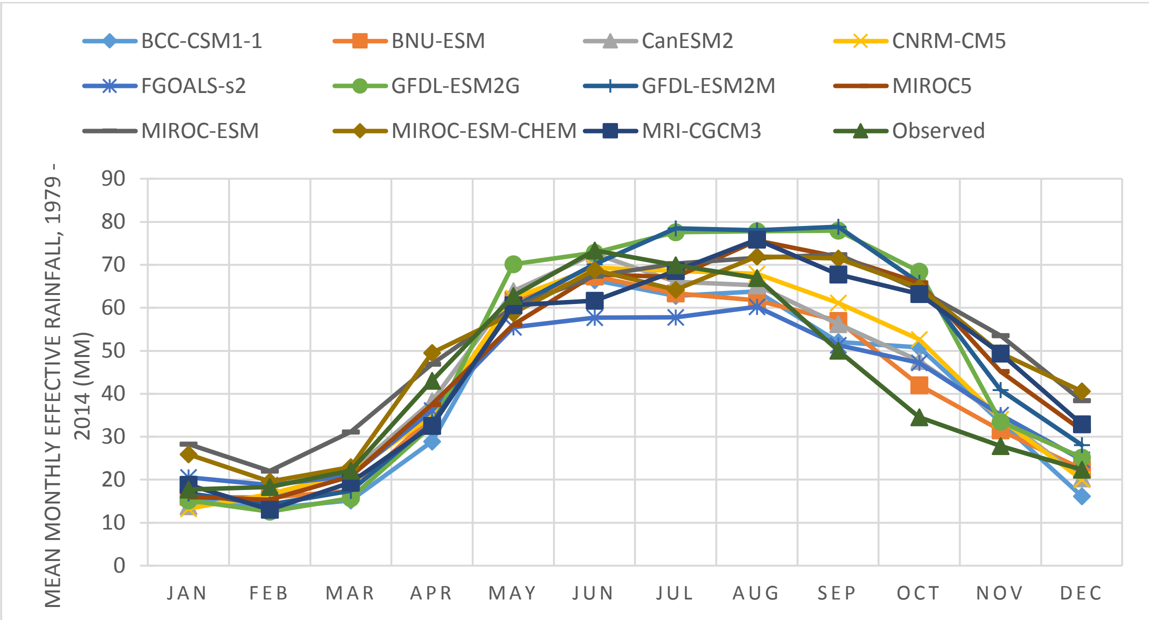

Figure 4.2: Monthly average effective rainfall for eleven GCMs plotted against observed values for the period between 1979 and 2013.

The monthly rainfall averaged from 1979 to 2014 for the six month period from May to October was analysed to determine which models predicted high, low and moderate average wet season monthly rainfall compared with observed rainfall trends over the same period. This was done in order to determine the model bias toward winter water availability (*Figure 4.3*), as the Berg River Catchment receives the bulk of its rain during winter.

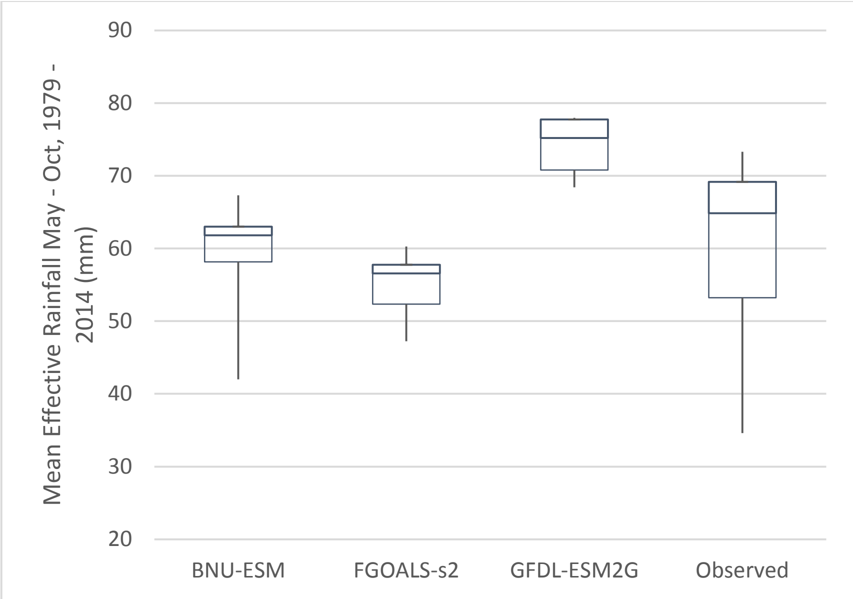

Figure 4.3: Box-plot of average wet season monthly rainfall data from eleven GCMs over the period from 1979 to 2014 compared with averaged monthly observed rainfall data from the same period.

The model which predicted the highest mean monthly effective rainfall over the selected period (74mm) was GFDL-ESM2G, while FGOALS-s2 had the lowest mean monthly effective rainfall prediction over the same period (55mm). BNU-ESM predicted the range of monthly effective rainfall values closest to the observed wet season average (60mm) with a mean of 59mm (*Table 4.3*).

Table 4.3: Average monthly rainfall for the period between 1979 and 2013 for three climate models compared with observed records averaged over the same period.

	BNU-ESM	FGOALS-s2	GFDL-ESM2G	Observed
Jan	15.97	20.55	16.8	17.69
Feb	15.89	18.78	14.2	18.29
Mar	17.39	20.89	17.43	22.1
Apr	34.69	36.08	33.22	43.05
May	61.89	55.48	60.16	62.77
Jun	67.31	57.68	70.14	73.32
Jul	63.35	57.78	78.51	69.91
Aug	61.74	60.25	78.05	66.97
Sep	56.99	51.31	78.87	50.05
Oct	41.99	47.23	65.82	34.59
Nov	31.5	35.05	40.89	27.83
Dec	22.51	24.64	28.06	22.32

In order to investigate and compare the numerical distribution of monthly averages over the period from 1979 to 2014 the data was plotted by quartiles for both the full year and for the six wettest months between May and October, (*Figures 4.3* & *4.4*). The root mean square errors (RMSE) were calculated for the full year for BNU-ESM, FGOALS-s2 and DFGL-ESM2G (*Table 4.4*).

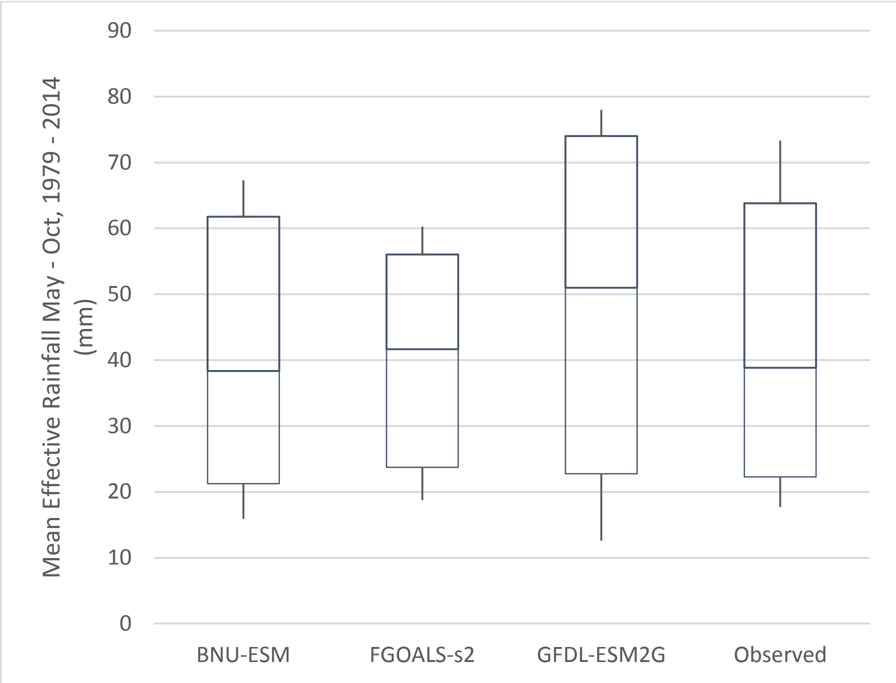

Figure 4.4: Box-plot of average full year monthly rainfall data from eleven GCMs over the period from 1979 to 2014 compared with averaged monthly observed rainfall data from the same period.

Table 4.4: Comparison of modelled climate rainfall data with observed rainfall records

	RMSE (mm)	Mean (mm)	Minimum (mm)	1st Quartile (mm)	Median (mm)	3rd Quartile (mm)	Maximum (mm)
BNU-ESM	5.2	40.93	15.89	21.23	38.34	61.78	67.31
FGOALS-s2	8	40.48	18.78	23.71	41.65	56.03	60.25
GFDL-ESM2G	14.1	48.29	12.61	22.77	50.96	73.99	77.98
Observed	0	42.41	17.69	22.26	38.82	63.82	73.32

It was found that BNU-ESM followed the observed distribution relatively closely in terms of derived annual effective rainfall over the period between 1979 and 2013, with a root mean square error (RMSE) of 5.2 mm, although displaying a slight downward shift in the minimum and maximum values. FGOALS-s2 and GFDL-ESM2G had smaller and larger distribution ranges, respectively, than the observed data, with both displaying a higher median. However, FGOALS-s2 was found to have a slightly lower mean than either the observed or modelled data. GFDL-ESM2G was found to have the largest distribution range, with the largest third quartile, the highest maximum value and the lowest minimum value.

Municipal records generally represent the most complete and current reference for commercial and residential water use at the scale of local government, which is why thes data were chosen for this project. Accurate and complete climatic records over a meaningful timeframe is only obtainable where such recordkeeping has consistently been done for a sustained period of time, which is why downscaled data has been used in this study. Using land use as a basis for the spatial anchoring of water requirements has the advantage of allowing for the disaggregated display of aspatial data, albeit simply averaged over a given area.

Access to reticulation schematics and water use records at the household level, or even at the neighbourhood or suburb level, would certainly improve model accuracy and would better demonstrate the spatial distribution of urban water demand. Locally measured evapotranspiration rates and estimated crop factors for major crop types would serve to further increase the accuracy of the simulated water demand within the local climatic context.

Chapter 5: Methodology

5.1 Introduction

Due to the magnitude of the current project, a suitable system design workflow needed to be established in order to ensure that evaluation and validation be done at regular intervals and according to an established schedule. For this project the V-model for systems design was followed as a basis for the system development lifecycle, as user requirements were fairly stable throughout the project and monthly team meetings facilitated a regular review process. This study covered the main decomposition and definition stages of system design, as well as the initial stages of integration and verification, including the development of a prototype.

Various different aspects of water requirements analysis and mapping at a catchment-level were investigated during the course of this project. These included the calculation of irrigation water demand for all major crops cultivated within the study area, the use of land use data as an ancillary dataset for dasymetric mapping of aspatial urban water use records, and the conceptual design of a spatial model capable of performing water demand calculations for the entire study area based on simple cartographic algebra.

Accepted urban growth rates from municipal records and data from climate models were used to assess the impact of predicted population growth, economic development and climate change on future water demand. Using the dasymetric approach, this data could then be displayed and analysed spatially.

The concept of spatial water requirements were formalised into types relating to land cover and associated activities, before being translated into grid-based components determined by the intended functionality of the model itself. Top-level and domain ontologies were established around the components of the model in terms of water use types and a land cover reclassification schema, while task ontologies and application ontologies were implemented in the form of specialised control components and components used in the calculation of irrigation requirements for the envisioned spatial model prototype. Heterogeneous data from several different sources were required, including a combination of time-series, cross-sectional and pooled datasets.

ESRI ArcMap's Model Builder application was used both in batch data preparation and processing, and as a basis for the prototype model design and production. Repetitive processing workflows using collections of moderately large datasets meant that running each processing tool series, or workflow, individually would be impractical and time-consuming. Several processing operations were therefore stringed together, iterating through multiple files within a designated workspace in order to save time and prevent user error.

The dasymetric method was applied in order to visualise the spatial distribution of urban water consumption, derived from a combination of spatial and aspatial datasets. The enumeration units were based on satellite-derived land use data, to which municipal water use records were linked, based on town cadastral outlines. irtual water was not considered in this project, as this project was focused on activities deriving water from local sources.

5.2 User Requirements

This study aimed to provide stakeholders with a more disaggregated spatial and temporal water requirements perspective, combining grid-based dasymetric mapping with bottom-up calculations, using a combination of cross-sectional, time-series and pooled data from various heterogeneous sources in order to give stakeholders a tool for predicting the nature of the spatial distribution of current and future water requirements within the study area as outlined in Chapter 1.

Through stakeholder interactions, by means of formal meetings and workshops, various user requirements were highlighted. Among these were the ability to (WRC Reference Group, 2015):

1. Visualise current water requirements spatially,
2. Model future water requirements based on changes in land cover and associated activities,
3. Model future water requirements based on specific climate change scenarios, and
4. View water demand at various user-specified levels of aggregation.

The envisioned functionality of the spatial water requirements model should allow for changes in land use to be implemented by altering simple binary determinant layers, while variations in future predicted climate should be achieved through the use of alternate climatic components.

5.3 Conceptual and Performance Baseline

5.3.1 Dasymetric Mapping of Urban Water Use Intensities

Validation and verification are described relative to system development processes as unique and separate activities. The verification of a system determines if that system meets with its original specification or design (*"Was the correct system built?"*), while the validation of a system determines whether or not it meets with the established user requirements (*"Does it function as required?"*) (Forsberg & Mooz, 1991). Both verification and validation are essential processes of systems design. This section discusses the application of the methodology proposed in *Section 5.2* to the datasets introduced in *Section 4.1*.

Water use may vary greatly in both spatial and temporal distributions. In order to connect the quantities and attributes of water use events with their physical locations the model had to be based on a spatial key. The distribution of land use and land cover types was chosen, as this offered the necessary distinction between residential and commercial land use types, and afforded a sufficient spatial resolution for more detailed dasymetric mapping.

The 2013 South African National land use dataset was used to define land use parcels in a uniform grid of 30 m by 30 m square pixels, or cells, each belonging to one of 72 original land use classes, of which 43 classes were counted as urban land use. The original land use types were reclassified to simplify the data such that it could be more readily compared with municipal water use records (*Table 5.1, Figure 5.1*).

Table 5.1: Reclassification of Land Use types.

Original Classes	New Land Use Type
1 - 9	Natural Vegetation
10 - 31	Cultivated
32 - 34	Forestry
35 - 39	Mining
40 - 41	Bare
42, 43, 52, 57 – 60, 69 – 72	Commercial
44 – 51, 53 – 56, 61 – 68	Residential

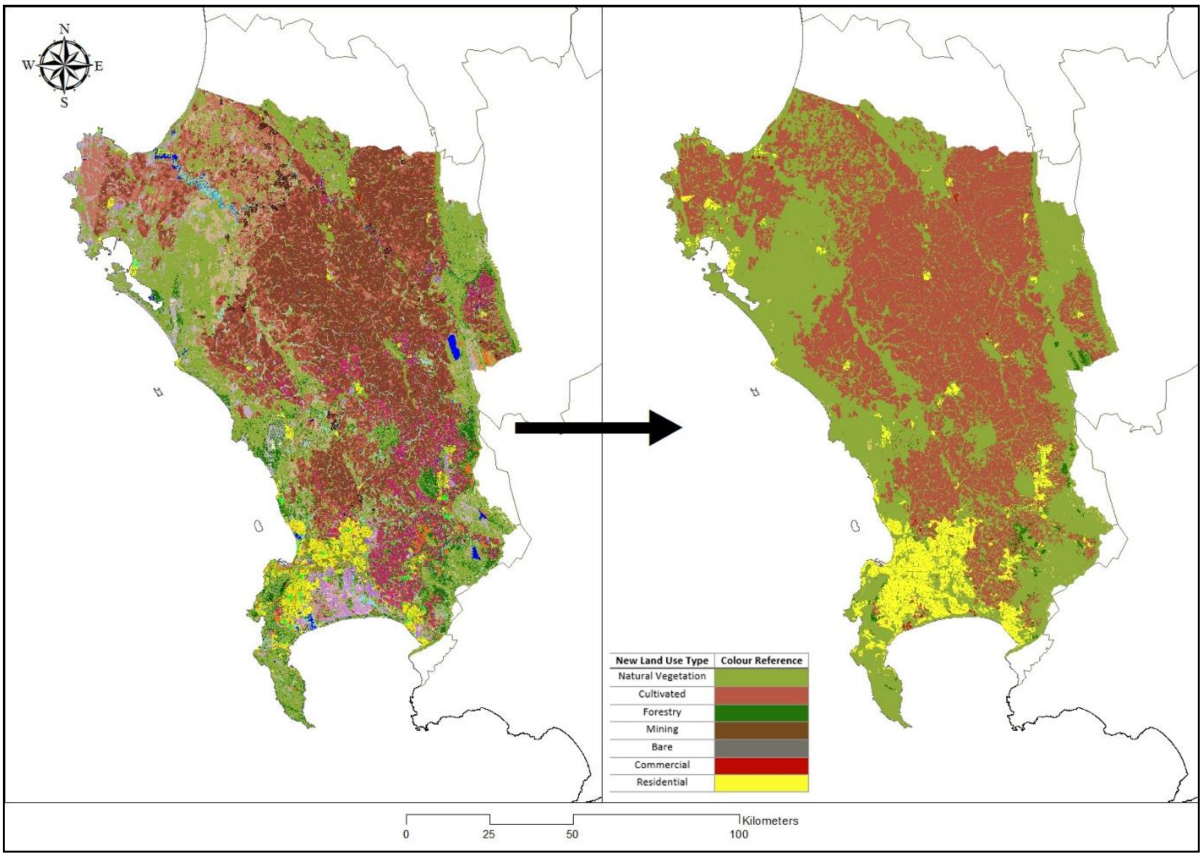

Figure 5.1: Reclassification of land use data in the study area from 72 classes to 8 classes (see Table 5.1 above).

Due to a lack of available data further subtypes of water use, such as varying levels of industrial and urban water use intensity were not defined. For this reason industrial intersectoral differentiation and separation between commercial and municipal water use was not done. After the land use had been reclassified the raster grid was converted into a point featureclass, producing an array of individual point features corresponding to the centroids of the cells in the original raster dataset. The points were then selected based on the land use type that they represent in order to remove non-urban points from the dataset. This was done to maximise processing efficiency during the following steps.

The creation of a point feature class was done in order to produce an attribute table with unique identifying numbers for each record representing a point feature. This would facilitate the assignment of unique attributes to each point, based on its location and land use type. Each point was assigned a Main Place ID number as well as a subcatchment ID number corresponding with its location. This was done to facilitate later queries and summaries based on point attributes and locations.

Urban water use records per town were obtained, including metered residential and commercial water consumption, as well as the total volume of water pumped into the system for each town (total system volume). Each point in the urban points layer was then assigned to either a residential or a commercial zone, based on it's location and the land use type that it represents (*Table 5.2*). Each zone was considered as a homogeneous areal unit with regards to urban water use. Cadastral town boundaries were used as a basis for zonal extents, such that all points in a given zone would be considered to fall within the same town.

Table 5.2: Zonal classification of towns

Residential Zone	Commercial Zone	Towns
RESBRG004	COMBRG004	Aurora
RESBRG003	COMBRG003	Dwarskersbos
RESBRG005	COMBRG005	Piketberg, Goedverwacht, Wittewater
RESBRG001	COMBRG001	Porterville, De Lust, Beaverlac
RESBRG002	COMBRG002	Velddrif
RESDRK002	COMDRK002	Gouda
RESDRK003	COMDRK003	Paarl, Wellington, Simondium, Water-Vliet, Val De Vie
RESDRK001	COMDRK001	Saron
RESSDA001	COMSDA001	Hopefield
RESSDA003	COMSDA003	Langebaan
RESSDA005	COMSDA005	Saldanha
RESSDA002	COMSDA002	St Helena
RESSDA004	COMSDA004	Vredenburg, Jacobsbaai, Paternoster, Louwville
RESSTL003	COMSTL003	Franschhoek, La Motte, Groendal
RESSTL004	COMSTL004	Klapmuts
RESSTL002	COMSTL002	Pniel, Kylemore, Groot-Drakenstein, Dwarsrivier
RESSTL001	COMSTL001	Stellenbosch, Elsenburg, Raithby, Lynedoch
RESSWR004	COMSWR004	Darling
RESSWR006	COMSWR006	Koringberg
RESSWR007	COMSWR007	Malmesbury, Chatsworth, Abbotsdale, Kalbaskraal
RESSWR005	COMSWR005	Moorreesburg, Klipfontein
RESSWR002	COMSWR002	Riebeek Kasteel
RESSWR001	COMSWR001	Riebeek West
RESSWR003	COMSWR003	Yzerfontein
RESWTZ001	COMWTZ001	Tulbagh

Each zone was then assigned both a commercial and a residential per-cell (or per-point) water consumption rate, depending on the total number of commercial and residential points withing each zone, as well as the overall consumption figures for each sector.

Direct abstraction points were mapped using the Water Authorisation Registration Management System (WARMS) dataset, which includes each abstraction point's coordinates, the water source, the registered annual abstraction volume, as well as administrative details pertaining to the registration and nature of the abstraction record.

Only direct abstraction for urban water use was mapped, excluding water services providers, as those volumes would be included in the bulk measurements within the reticulation systems included in the total system volume obtained from local municipalities.

A non-spatial database was designed in order to contain and interlink the desired data (*Figure 5.2*). The *Land_Use* table would form the central part of the database, containing each cell's unique identifier (*Cell_ID*), corresponding quaternary cathment (*QC_ID*), Main Place (*MP_ID*) and land use class and subclass (*LU_Class* and *LU_Subclass*, respectively). This would enable a user to search for and select any datapoints located within a given area as defined by their attributes.

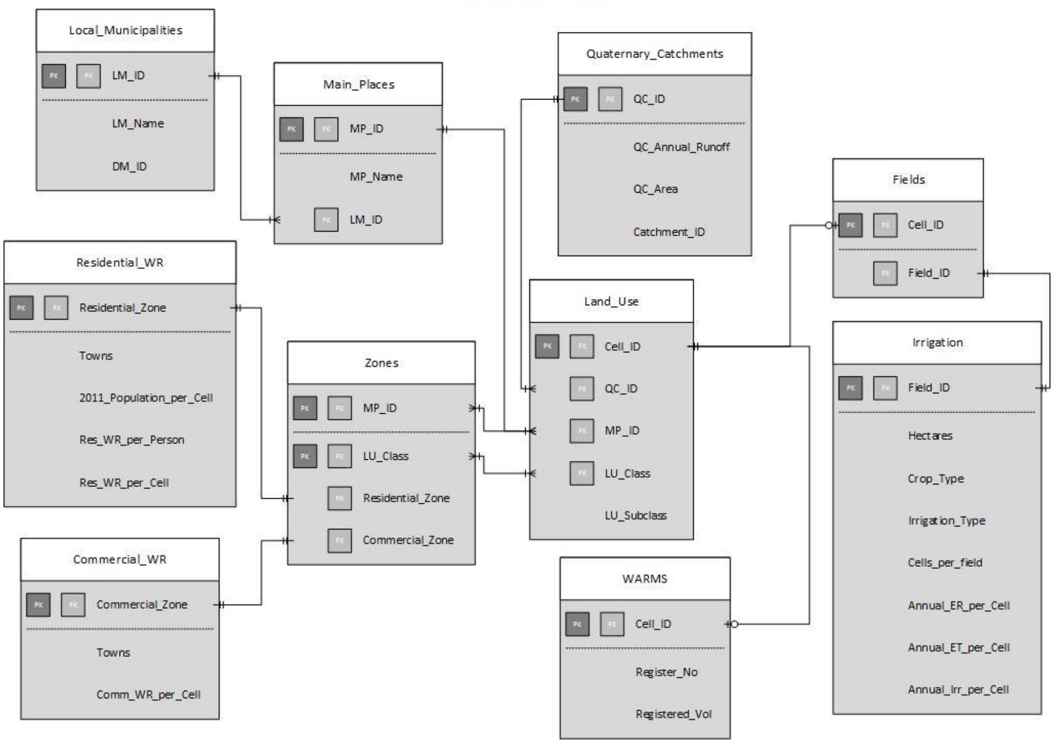

Figure 5.2: Relational database structure storing water requirements data used to assign specific water requirements to point array.

The *Quaternary_Catchments*, *Main_Places* and *Local_Municipalities* tables contained further details about the specific spatial context of each point, such as the names corresponding with identification codes, as well as quaternary catchment annual runnof in milimeters, while the *Zones* table contained a zonal classification grouping points by land use type and physical location in order to assign specific per-cell water use rates to each point feature.

Each zone, both residential and commercial, was linked with a table detailing the associated water requirements, as simulated from collected data. The calculated water requirements for each zone, as well as further details about that zone were contained in the two water requirements tables (*Residential_WR* and *Commercial_WR*).

The *Residential_WR* table contained a list of towns located within each zone, the net population of each zone based on 2011 national census data, the per capita residential water requirements based on water use records, as well as the calculated residential water requirements per cell. Similarly, the *Commercial_WR* table contained a list of towns defined by each commercial zone, as well as the calculated commercial water requirements per cell, based on commercial water use records.

A *Fields* table was created, containing the field identification number corresponding to each cell located within an irrigated field. The *Fields* table was then linked with an *Irrigation* table, detailing the characteristic attributes of each field, including the total field size in hectares, the main crop type, irrigation type, the number of cells per field, the annual effective rainfall per cell, the annual evapotranspiration per cell, and the annual irrigation per cell.

In order to obtain estimates for urban water usage, data from municipal water use records (Drakenstein, Stellenbosch, Swartland, Saldanha Bay and Bergrivier Municipalities, 2015) were used. The period of July 2010 to June 2011 was chosen to match population records from the 2011 national census (StatsSA, 2012). As water use was recorded per town, certain peri-urban settlements were grouped with larger towns in their proximity to make up urban zones.

The total urban population for each zone was calculated, as well as the number of residential and commercial land use cells within each zone. Per-cell and per-capita water use were then calculated for each zone, using residential water use from municipal water use records (*Table 5.3*). Commercial water use per cell was calculated using the total commercial water use per zone.

Table 5.3: Per-capita water use and total number of residential cells for each residential zone (source: Bergrivier, Drakenstein, Stellenbosch, Swartland and Saldanha Bay municipalities (2015)).

Residential Zone	Towns	Per-Capita Water Use ($m^3/c/a$)	Residential Cell Count
RESBRG004	Aurora	71.31	501
RESSWR004	Darling	202.66	2 592
RESBRG003	Dwarskersbos	66.72	487
RESSTL003	Franschhoek, La Motte, Groendal	105.08	2 466
RESDRK002	Gouda	57.74	373
RESSDA001	Hopefield	164.95	3 657
RESSTL004	Klapmuts	69.78	633
RESSWR006	Koringberg	94.65	528
RESSDA003	Langebaan	69.14	8 609
RESSWR007	Malmesbury, Chatsworth, Abbotsdale, Kalbaskraal	148.29	8 680
RESSWR005	Moorreesburg, Klipfontein	122.5	3 139
RESDRK003	Paarl, Wellington, Simondium, Water-Vliet, Val De Vie	49.73	32 320
RESBRG005	Piketberg, Goedverwacht, Wittewater	124.66	2 808
RESSTL002	Pniel, Kylemore, Groot-Drakenstein, Dwarsrivier	48.51	1 334
RESBRG001	Porterville, De Lust, Beaverlac	83.15	1 895
RESSWR002	Riebeek Kasteel	92.81	918
RESSWR001	Riebeek West	91.2	1 166
RESSDA005	Saldanha	59.45	4 161
RESDRK001	Saron	49.38	1 985
RESSDA002	St Helena	92.01	4 113
RESSTL001	Stellenbosch, Elsenburg, Raithby, Lynedoch	46.24	11 921
RESWTZ002	Tulbagh	283.03	1 820
RESBRG002	Velddrif	76.05	3 107
RESSDA004	Vredenburg, Jacobsbaai, Paternoster, Louwville	137.25	7 499
RESSWR003	Yzerfontein	121.28	2 369

To obtain a residential water use per cell value (R_C), the total annual residential billed metered water use for each zone (R_Z) was divided by the number of residential cells within that zone (N_{RZ}). The total annual commercial billed metered water use for each zone (C_Z) was similarly divided by the number of commercial cells within that zone (N_{CZ}) to obtain a commercial water use per cell value (C_C):

$$R_C = \frac{R_Z}{N_{RZ}} \tag{4}$$

$$C_C = \frac{C_Z}{N_{CZ}} \tag{5}$$

Future urban water demand was calculated using population growth rates from the All Towns Reconciliation Strategies Reports based on three main population and water demand growth scenarios (DWA, 2011).

In order to produce the binary determinant component layers for the urban module of the water requirements model, a simple reclassification process was be required. For the residential determinant layer all land use categories were reclassified to a value of zero, apart from residential land use, which was reclassified to a value of one. The commercial determinant layer was created in a likewise manner, assigning zero values to all non-commercial land use, and values of one to all commercial land use cells.

5.3.2 Estimating Field-Level Irrigation Requirements

In order to map irrigated agriculture in a manner consistent with the land use mapping approach taken for delineating urban water use zones, a polygon feature class dataset from the Western Cape Department of Agriculture's 2013 Crop Census was obtained, defining the borders of all cultivated fields in the study area (DoA, 2013). The dataset was converted into a raster grid coincident on the national land use dataset used previously, with matching spatial extent and cell sizes, such that the cells within each dataset would be conterminous.

The resulting agriculture raster grid was then converted to a points feature class producing an array of points, each located at the center of a grid cell. Attributes defining the field identification number, predominant crop type, irrigation method and total field size in hectares were then assigned to each point based on the properties of the field which overlaid it.

Monthly irrigation requirements were calculated at a field level using a modified Penman-Monteith formula (FAO, 1992) reference crop evapotranspiration values based on a 50-year climate dataset (Shulze *et al.,* 2007) and locally and internationally derived crop coefficients, spanning sixteen different crop categories. The original Penman-Monteith formula can be summarised as follows (Monteith, 1965):

$$E_T = \frac{\Delta R_n + (e_a - e_d) \times \frac{\rho \times c_p}{r_a}}{\lambda\left(\Delta + \gamma \times \left(1 + \frac{r_s}{r_a}\right)\right)} \quad (6)$$

where R_n is net radiation (W/m^2), ρ is air density, c_p is the specific heat of air, r_s is net resistance to diffusion through the surfaces of leaves and soil (s/m), r_a is the net resistance to diffusion through the air from the surface to the height of the measuring instruments (s/m), γ is the hygrometric constant, $\Delta = de/dT$, e_a is saturated vapour pressure at air temperature, and e_d is the mean vapour pressure. This method is generally considered to be accurate, although r_s may become inaccurate when a large region is considered, or if vegetation is diverse or distributed in an uneven manner (Kneale, 1991). The revised version of the formula is as follows (FAO, 1992):

$$E_T = \frac{0.408 \times \Delta R_n + u^2 \times (e_a - e_d) \times \gamma \times \frac{900}{T_{xd} + 273}}{\Delta + \lambda(1 + 0.34 \times u^2)} \quad (7)$$

where T_{xd} is mean monthly temperature.

Effective rainfall (*ER*), calculated using the U.S. Bureau of Reclamation Method (Stamm, 1967) (*Table 5.4*) was used to estimate soil moisture deficit. Stevens (2007) found that farmers preferred to irrigate based on accumulated knowledge and experience rather than by physical measurement. For this reason effective rainfall was treated as a displacing factor in irrigation demand.

Table 5.4: Effective rainfall estimates based on accumulated rainfall using the U.S. Department of Reclamation Method (Adapted from Adnan & Khan, 2009)

Precipitation Increment Range (mm)	Percentage of Rainfall Considered Effective	Effective Precipitation Accumulated Range (mm)
0.0 – 25.4	90 – 100	22.9 – 25.4
25.4 – 50.8	85 – 95	44.4 – 49.5
50.8 – 76.2	75 – 90	63.5 – 72.4
76.2 – 101.6	50 – 80	76.2 – 92.7
101.6 – 127.0	30 – 60	83.8 – 107.9
127.0 – 152.4	10 – 40	86.4 – 118.1
> 152.4	0 – 10	86.4 – 120.6

The methodology for determining actual evapotranspiration levels (ET_a, mm/day) was adapted from Allen *et al*. (1998):

$$ET_m = K_{cm} \times ET_{om} \quad (8)$$

where ET_m is the monthly evapotranspiration value calculated by multiplying the reference evapotranspiration value for a given month, ET_{om} (mm/day) by the crop coefficient for the corresponding crop and season, K_{cm} (Mekonnen & Hoekstra, 2011). From this simplified equation the potential amount of water that could be taken up by a plant may be calculated for each month. *Table 5.5* lists the crop coefficients used in this study.

Table 5.5: Seasonal time-averaged crop coefficients (K_c) for each irrigated crop type.

Crop Types:	**Reference Crop Coefficient (K_c)**				**Reference:**
	Summer Dec-Feb:	**Autumn Mar-May:**	**Winter Jun-Aug:**	**Spring Sept-Nov:**	
Berries	0.8	0.33	0.2	1	SAPWAT (Van Heerden et al.)
Citrus Fruits	0.80	1.28	0.79	0.62	Green and Moreshet (1979)
Winter Grains	-	-	0.92	0.25	Allen *et al.* (1998)
Grapes	0.95	0.55	0	0.59	SAPWAT (Van Heerden et al.)
Herbs/Essential Oils	0.75	-	-	1.15	Allen *et al.* (1998)
Nuts	1.10	0.65	0.50	1.10	Allen *et al.* (1998)
Oil Seeds	0.35	-	-	1.15	Allen *et al.* (1998)
Other Crops	0.35	-	-	1.15	Allen *et al.* (1998)
Pepo	0.75	-	-	1.05	Allen *et al.* (1998)
Planted Pastures	1.25	1.05	0.90	1.06	Allen *et al.* (1998)
Pome Fruit	0.77	0.72	0.19	0.46	Taylor & Gush (2014)
Prickly Pears	0.47	0.47	0.47	0.47	Allen *et al.* (1998)
Stone Fruit	0.85	0.28	0	0.72	SAPWAT (Van Heerden et al.)
Sub-Tropical Fruit	0.80	0.70	0.40	0.70	Allen *et al.* (1998)
Tree Fruit (Other)	0.99	0.60	0.45	0.62	Allen *et al.* (1998)
Vegetables	0.75	-	-	1.15	Allen *et al.* (1998)

Crop coefficients were based on three-monthly seasons, and were adapted by time-averaging. The difference between the monthly effective rainfall (ER_m) and the monthly evapotranspiration (ET_m) represents the soil water deficit to be covered by irrigation, which is then converted into monthly irrigation requirement:

$$I_m = 100(\frac{10\mathrm{A}((ET_m - ER_m)}{EF}), I_m > 0 \quad (9)$$

where I_m is the monthly irrigation requirement, A is the field area in hectares, and EF the irrigation efficiency (*Table 5.6*). Negative values were treated as zero irrigation requirements, as it was assumed that plants cannot utilise water beyond the point at which potential evapotranspiration is reached.

Table 5.6: Irrigation types found in the study area with relative efficiencies (Source: DoA Elsenberg, Ascough & Kiker, 2002).

Irrigation Type	Efficiency %	Irrigation (m^3/a)
Dragline irrigation	75	61 160
Drip irrigation	85	437 962 576
Flood irrigation	65	5 464
Floppy irrigation	85	20
Pivot irrigation	85	14 759 581
Sprinkler irrigation	75	5 810 051
Total		458 598 854

Once the monthly irrigation requirement for each field in the 2013 agriculture census flyover dataset had been calculated, the field polygons were converted to grid-based cells, coincident on the land use grid used for the spatial delineation of urban water use. A per-cell irrigation requirement was then calculated per field following a similar methodology as with the calculations of per-cell urban water use (*Equations 4 & 5*). Once the per-cell values were calculated for urban residential, urban non-residential (commercial) and irrigated land uses, each point was assigned a water requirements value based on its land use type and location. The point array was then converted back into a grid-based map to facilitate visual analysis and processing efficiency.

Due to the number of measurements involved in calculating the Penman-Monteith reference crop potential evapotranspiration rate (*PE*), an alternative formula was used to estimate future crop water requirements, based on average temperatures and effective rainfall values. The Thornthwaite method (Thornthwaite, 1948) (*Equations 10, 11 & 12*) was chosen as it manages to provide an estimate for potential evapotranspiration from monthly temperature averages:

$$PE_m = 16N_m\left(\frac{10\bar{T}_m}{I}\right)^a \tag{10}$$

where *m* denotes the respective month, N_m is the adjustment factor representing hours of daylight, T_m is the monthly mean temperature, *I* is the heat index for the year:

$$I = \sum i_m = \sum \left(\frac{T_m}{5}\right)^{1.5} \qquad (11)$$

and: $a = 6.7 \times 10^{-7} \times I^3 - 7.7 \times 10^{-5} \times I^2 + 1.8 \times 10^{-2} \times I + 0.49$ (12)

A baseline comparison dataset was calculated to determine how the simpler Thornthwaite formula would compare with the Penman-Monteith method for calculating evapotranspiration. The baseline reference crop potential evapotranspiration rates were used to calculate a simple calibration factor in order to adjust E_{Tm} values calculated using the Thornthwaite equation based on projected future climate conditions:

$$F_{cm} = \frac{E_{Tm}}{PE_m} \qquad (13)$$

Figure 5.3 shows the distribution of the resulting calibration factors. New irrigation requirements were then calculated based on the adjusted *PE* values, using the crop factors and methodology described above (*Tables 5.5 & 5.6, Equations 8, 9 & 10*).

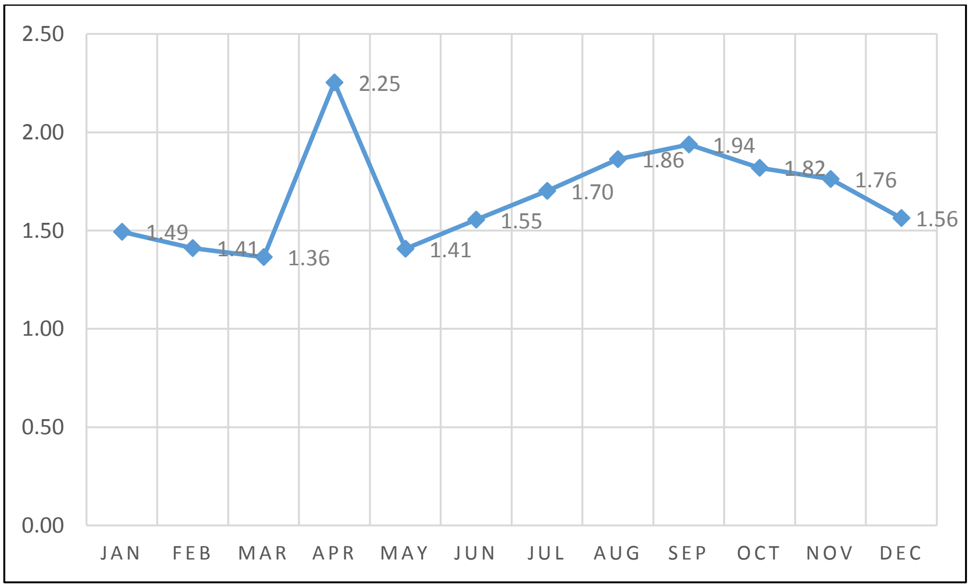

Figure 5.3: Distribution of average monthly E_{Tm}/PE_m ratios (source: DoA Elsenburg, own calculations).

In *Figure 5.4* the monthly average ratios between the Penman-Monteith and Thornthwaite evapotranspiration figures show a distinctly seasonal trend, with an outlier in the April average ratio. September represents the month where the ET_m value is largest relative to the PE_m value, while March represents the month where the two estimates are closest.

Figure 5.4 shows a comparison between the reference crop ET figures obtained from the South African Agrohydrological Atlas, calculated using the Penman-Monteith method, and PET values calculated using the Thornthwaite method. The ET values were calculated from temperature averages based on a 50-year dataset from 1950 to 1999, while the PET values were calculated based on temperature averages over a 35-year period from 1979 to 2013.

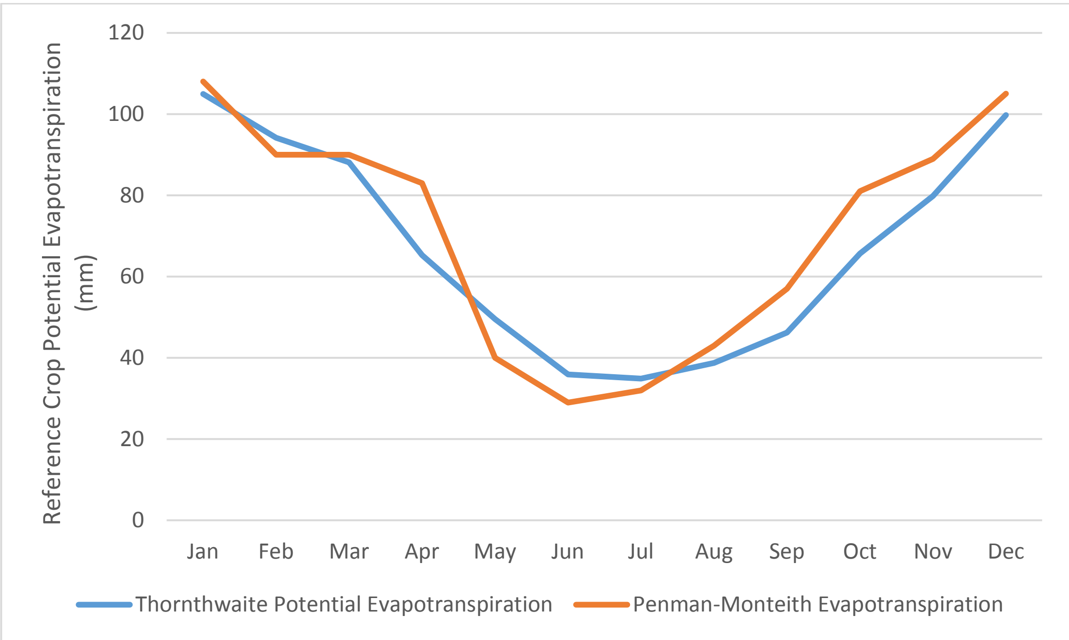

Figure 5.4: Comparison of historic monthly averages for potential reference crop evapotranspiration over the study area calculated using the modified Penman-Monteith method over a 50-year period (1950 – 1999) and the Thornthwaite method over a 35-year period (1979 – 2013). Penman-Monteith evapotranspiration values were taken from the WRC's Agrohydrological Atlas, while average monthly temperature data consisted with prediction models were used for the Thornthwaite calculations, hence the discrepancy in time periods.

While the different temporal spans of the two datasets were anticipated to result in different monthly averages, the different trends suggest an explanation for the distribution of the calibration factors for the month of April, as the Thornthwaite evapotranspiration value declines suddenly during March, while the Penman-Monteith evapotranspiration value remains relatively stable, only declining similarly during April.

5.3.3 Calculated Water Requirements and Verification of Results

In order to verify the approach taken to map water requirements a baseline dataset was established using the methodology outlined above. Monthly water use trends were also investigated in order to better visualise the temporal distribution of water use. In order to verify calculated irrigation water requirements a sample area (*Figure 5.5*) was used in a comparison with the calculated irrigation requirements from the Water Availability Assessment Study's (WAAS) Water Resource Yield Model (WRYM) and Water Resource Simulation Model (WRSM). A total irrigation requirement of 122 million m^3/a and a total evaporation 207 million m^3/a were found based on the methodology and data discussed in previous chapters, while the WRSM estimate of irrigation requirements was found to be 200 million m^3/a (*Table 5.7*).

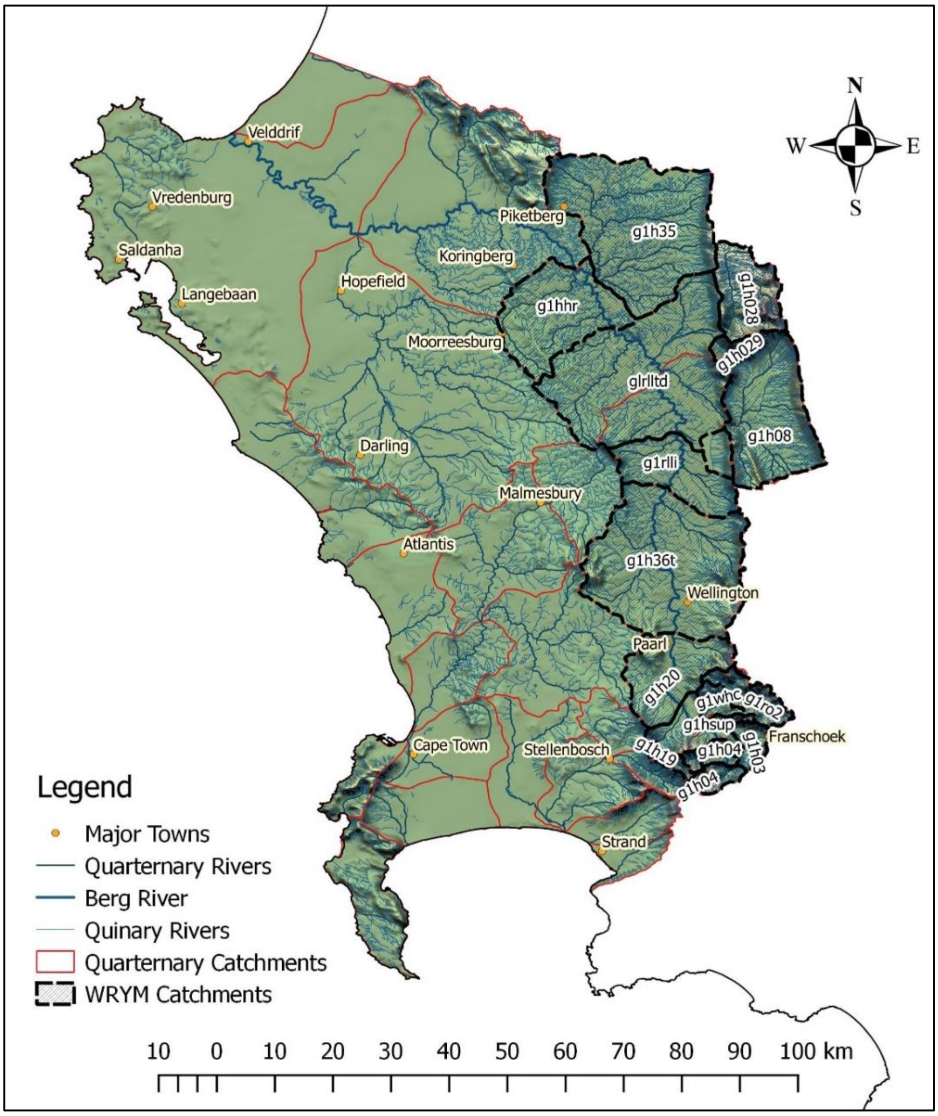

Figure 5.5: WRYM/WRSM sample region in the Berg Water Management Area.

Table 5.7: Comparison of registered direct abstraction for irrigation, WRSM irrigation requirement estimates, farm dam capacity and irrigation requirements and evapotranspiration rates calculated in this study in a sample area (source: own calculations, WARMS registry, Water Resource Simulation Model).

WRSM Catchment	Calculated Irrigation Requirements (m^3)	Calculated Evapotranspiration (m^3)	WRSM Irrigation Demand (m^3)	WARMS Abstractions for Irrigation (m^3)	Farm Dam Capacity (m^3)
G1H028	279 000	335 000	120 000	60 000	0
G1H029	23 000	29 000	160 000	938 000	9 241 096
G1H03	5 878 000	8 214 000	5 950 000	3 800 000	1 260 259
G1H08	22 501 000	28 518 000	24 750 000	23 684 000	14 525 464
G1H19	1 041 000	1 487 000	550 000	3 395 000	4 415 202
G1H20	33 555 000	47 163 000	59 830 000	18 944 000	13 950 173
G1H35	5 544 000	6 525 000	5 530 000	26 803 000	5 514 640
G1H36T	93 214 000	126 182 000	74 270 000	54 471 000	28 463 516
G1HSUP	7 909 000	11 176 000	8 260 000	7 051 000	0
G1RLLI	13 681 000	16 077 000	14 460 000	2 423 000	7 361 015
G1WHC	1 134 000	1 587 000	4 870 000	142 000	0
G1RLLTD	29 004 000	34 994 000	2 200 000	2 439 000	2 846 799
Total	213 761 000	282 287 000	**200 950 000**	**144 150 000**	**87 578 162**

Calculated evapotranspiration values were found to resemble total irrigation demand for the sample region as calculated by the WRSM more closely than calculated irrigation based on effective rainfall. The reason for the differences may be due to additional factors that are considered within the WRSM estimates, such as soil salinity control and evaporation from irrigation channels, as well as the impacts of soil types on soil water availability (Bailey, 2008). On farm storage capacity was also included in the WRSM calculation of irrigation demand as intercepted water removed from the system for irrigation purposes.

Table 5.8 and *Figure 5.6* show a comparison between registered direct abstraction from the WARMS dataset and calculated evapotranspiration and irrigation values per local municipality. It was found that total registered abstraction falls well below the irrigation requirements and potential plant evapotranspiration, indicating that registered abstraction values may be conservative estimates relative to actual use.

Table 5.8: Comparison of irrigation requirements and potential evapotranspiration calculated in this study with registered direct abstraction for agricultural use per local municipality.

	Irrigation Requirement (m^3/a)	Evapotranspiration (m^3/a)	WARMS Registered Abstraction (m^3/a)
Bergrivier	40 180 618	47 994 094	44 121 078
City of Cape Town	37 257 395	56 143 556	23 310 479
Drakenstein	143 595 087	195 657 080	101 917 061
Saldanha Bay	441 143	875 637	1 177 949
Stellenbosch	99 244 570	147 555 542	124 434 090
Swartland	115 379 133	143 207 759	22 692 626
Witzenberg	22 500 909	28 518 124	22 269 927
Total	458 598 855	619 951 792	**339 923 211**

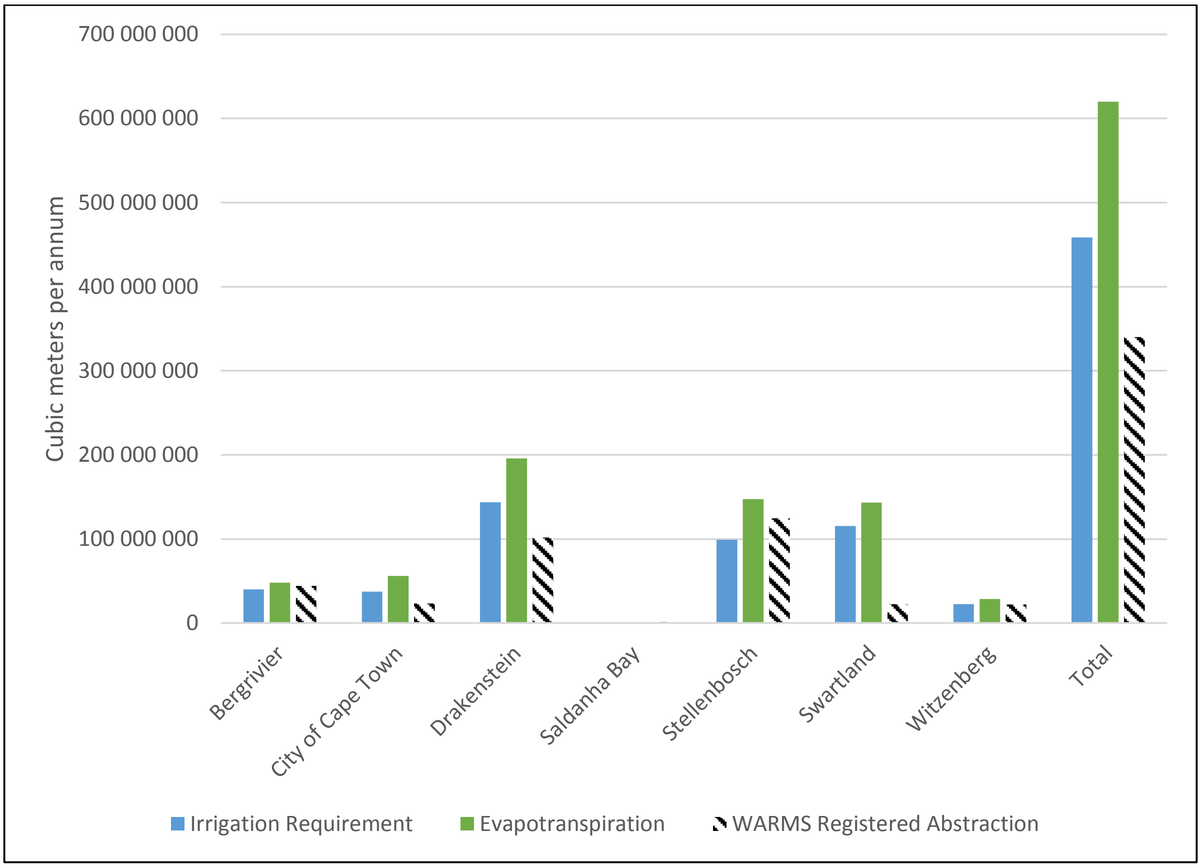

Figure 5.6: Comparison of calculated irrigation requirements and potential evapotranspiration values with registered direct abstraction for agricultural use per local municipality.

It is worth noting that registered abstraction figures from the WARMS dataset do not reflect actual abstraction, but serves as a rough estimate of anticipated use. Where municipalities (for example Bergrivier and Stellenbosch) showed registered abstraction values above calculated irrigation requirements, this may be indicative of water used for other practices, such as salinity control or over irrigation.

A comparison between irrigation demand calculated using reported actual field sizes and field sizes based on number of grid cells in the rasterised dataset was done in order to investigate the effects of rasterisation on calculated irrigation requirements. *Figure 5.7* shows the results of the comparison. It was found that a total field size difference of 945.16 ha, or 1.26% resulted from the conversion from vector to raster, as well as a 5.5 million m^3, or 1.01% increase in calculated irrigation water requirements.

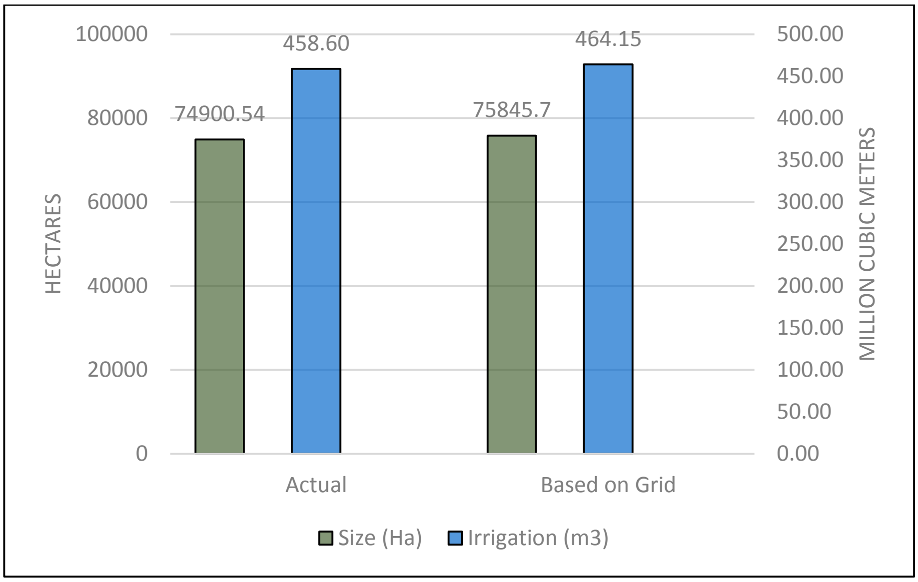

Figure 5.7: Comparison of total cultivated field size and total calculated irrigation requirements based on actual measured field size and fields converted to grid cells (source: DoA Elsenberg, own calculations).

The model comprised a set of parallel modules (*Figure 5.8*), each handling a specific water use sector. Urban water requirements was calculated separately from irrigation water requirements, using a separate methodology as outlined in the following sections. The results from each module's calculations were incorporated into a single data product that could be viewed cartographically or used to derive tabularised statistics and summaries.

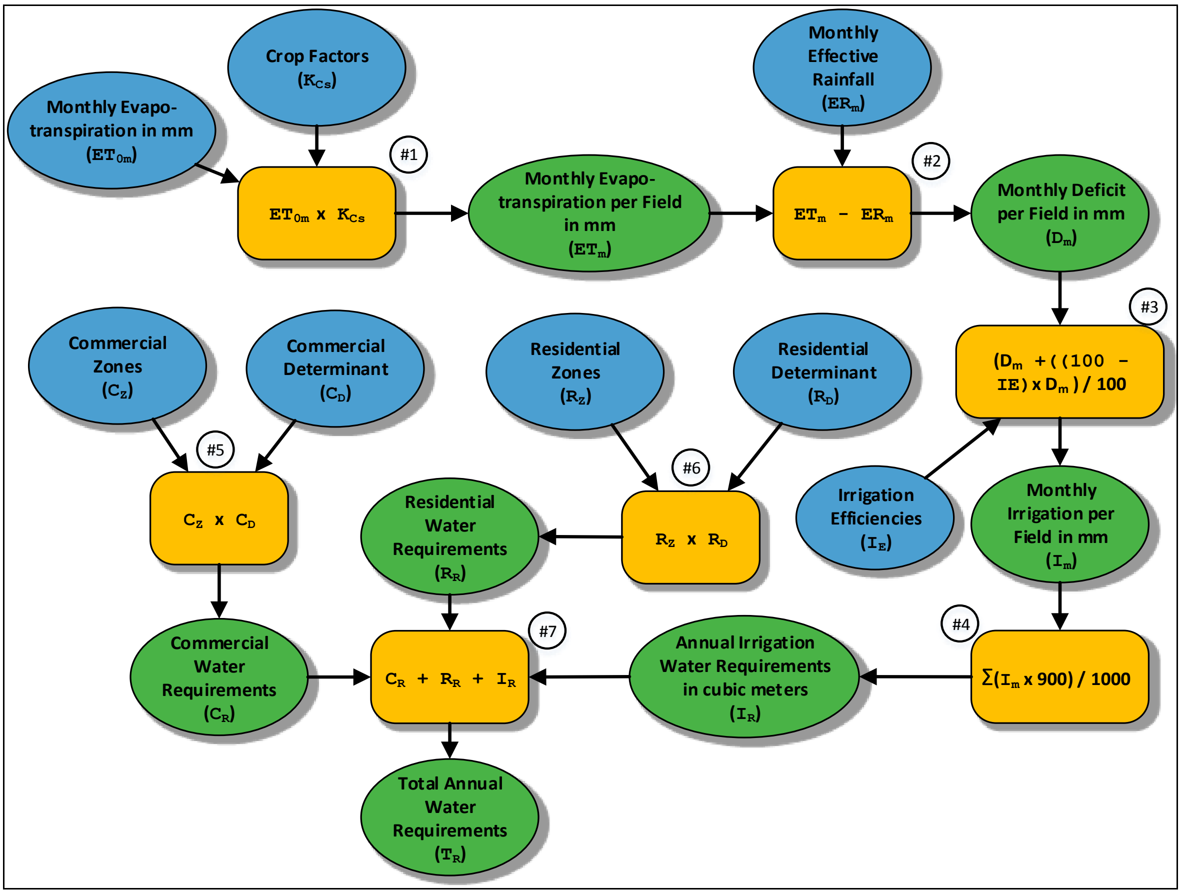

Figure 5.8: Visual representation of the raster-based water requirements model, using ESRI ArcMap's Model Builder application.

The model design enabled dynamic changes to land use to be made, and the resulting effects of local and regional water requirements to be examined. In order to accomplish this, the model consisted of a series of continuous zones delineating homogeneous rates of water consumption associated with various sectors of land and water use characterising each urban centre. Urban land use was classified as either residential or commercial. *Table 5.9* summarises the component layers used in the water requirements model calculations.

Table 5.9: Component layers of water requirements model

Component	Module	Format	Description
Residential Zones ($\boldsymbol{R_Z}$)	Urban	Raster	Continuous surface interpolated from urban centres containing monthly per-cell water use rates associated with each residential zone, based on pooled data.
Commercial Zones ($\boldsymbol{C_Z}$)	Urban	Raster	Continuous surface interpolated from urban centres containing monthly per-cell water use rates associated with each commercial zone, based on pooled data.
Residential Binary Determinant Layer ($\boldsymbol{R_D}$)	Urban	Raster	Continuous surface derived from cross-sectional land use comprised of ones and zeroes, representing residential (ones) and non-residential (zeroes) land use per cell.
Commercial Binary Determinant Layer ($\boldsymbol{C_D}$)	Urban	Raster	Continuous surface derived from cross-sectional land use comprised of ones and zeroes, representing commercial (ones) and non-commercial (zeroes) land use per cell.
Seasonal Crop factors ($\boldsymbol{K_{Cs}}$)	Irrigated Agriculture	Raster	Continuous surface derived from pooled data on main crop types per irrigated field, containing relevant seasonal crop factors for each irrigated field.
Irrigation Efficiencies ($\boldsymbol{I_E}$)	Irrigated Agriculture	Raster	Continuous surface derived from cross-sectional data on irrigation methodology per irrigated field containing irrigation efficiency factors for each irrigated field.
Monthly Reference Crop Evapotranspiration Rates ($\boldsymbol{ET_{0m}}$)	Irrigated Agriculture	Raster	12-monthly time-series continuous surface data containing reference crop evapotranspiration rates derived from interpolated monthly average temperatures
Monthly Effective Rainfall ($\boldsymbol{ER_m}$)	Irrigated Agriculture	Raster	12-monthly time-series continuous surface data containing monthly effective rainfall interpolated from daily rainfall observations

The spatial water requirements model consisted of a series of congruent raster (grid-based) layers, based on the South African National Land Use/Cover dataset of 2013, and a polygon feature class of irrigated fields, which had been converted to a raster grid using the land cover dataset as a reference raster, overlaid to produce a final result. Each component layer had the exact same cell size and grid placement geometry, such that the respective cells align spatially. Layers were combined in a series of steps, based on the design in *Figure 5.1*.

Total annual irrigation demand (I_R) is calculated by incorporating climatic data in the form of monthly reference crop evapotranspiration rates (ET_{0m}), derived from temperature observations (*Equations 14, 15, 16 & 17*), and monthly effective rainfall (ER_m), derived using the methodology discussed in section *5.2.2*.

Seasonal crop coefficients (K_{Cs}), corresponding to each crop type, were used to create a grid-based layer for each season, where cells not containing irrigated land use were given a NULL value. Each cell falling within an irrigated field was given the value of the crop factor corresponding with the primary crop type grown in that field for each respective season (*Table 5.5*).

Monthly evapotranspiration per field (ET_m) was calculated by combining each of the monthly ET_{0m} values with the corresponding K_{Cs} value in *Step #1*. The monthly soil water deficit (D_m) was then calculated as the difference between the monthly evapotranspiration and the monthly effective rainfall layers in *Step #2*:

$$ET_m = ET_{0m} \times K_{Cs} \tag{14}$$

$$D_m = ET_m - ER_m \tag{15}$$

Irrigation efficiencies based on reported irrigation methods were incorporated into the model by designating a factor corresponding to the irrigation method used for each cell using the percentages listed in *Table 5.6*. Cells that represent land use other than irrigated agriculture were given a NULL value. The resulting irrigation efficiency layer (I_E) was used to calculate the monthly irrigation per field in millimetres (I_m) in *Step #3*:

$$I_m = D_m \left(1 + \frac{100 - I_E}{100}\right) \tag{16}$$

The total annual irrigation requirements for each cell in cubic meters (I_R) was calculated in *Step #4* as follows:

$$I_R = \sum \frac{I_m \times 900}{1000} \tag{17}$$

Urban water requirements were calculated based on land use and observed water use rates. The study area was subdivided into zones of relatively homogenous urban water use. Each zone was based around an urban centre, from which two grid-based layers were derived – a residential zones layer (R_Z) and a commercial zones layer (C_Z). The cells within each zone were assigned values corresponding with the average per-cell water use rate, as calculated for existing urban land use, within that zone.

Two binary determinant layers were then created in order to mask the zone layers such that only cells with the relevant land use type remain within each zone. The determinant layers consisted of cells with a default value of zero, with values of one assigned to cells corresponding to the appropriate land use type. In *Step #5* and *Step #6* urban water requirements were calculated as:

$$C_R = C_Z \times C_D \tag{18}$$

$$R_R = R_Z \times R_D \tag{19}$$

where C_R is the commercial requirement, R_R the residential requirement, and C_D and R_D are the commercial and residential determinant layers respectively. The total water demand for all sectors in the study area (T_R) was then calculated in *Step #7* as:

$$T_R = C_R + R_R + I_R \tag{20}$$

5.4 Model Prototype

Following data validation and the design of the basic model structure a prototype is produced to demonstrate the intended functionality of the model. Model components are constructed as per *Table 5.1* and combined in a linear workflow based on the design in *Figure 5.1*. Main data products of the prototype include monthly deficit estimates for irrigated crops in millimetres, total annual irrigation requirements and overall annual commercial and residential water requirements, based on all non-residential urban and residential billed metered data, respectively. The model outputs are in the form of grid-based raster layers with a cell size of 30m x 30m, which may then be aggregated to any areal unit as desired by the user.

All input data converted to model components can be designated as parameters that may be altered or replaced with suitable data, such as updated urban zones, land use or climatic data. The spatial grid upon which the model is based allows for uniformity in data components by allocating the original land use layer as a snap raster, which, along with designating the appropriate cell size, produces perfectly coincident gridded datasets that form the foundation of the model concept.

Chapter 6: Results and Discussion

6.1 Baseline Water Requirements

Billed metered urban water consumption was found to follow a marked seasonal trend (*Table 6.1*, *Figure 6.1*), with peak consumption during February and March. This may be due to increased watering of gardens and recreational use, such as cleaning and replacing water from swimming pools, during warm and dry months. Municipalities with high average urban water consumption appear to exhibit seasonal peaks of greater magnitude than those with low average urban consumption.

Table 6.1: Monthly urban billed metered water consumption (residential and business consumption), including (right) and excluding (left) the City of Cape Town, from July 2010 until June 2011. Months with the lowest consumption rates are highlighted in blue, while months with the highest consumption rates are highlighted in orange (source: Bergrivier, Drakenstein, Stellenbosch, Swartland and Saldanha Bay municipalities, City of Cape Town Metro (2015)).

Month (2010 - 2011)	Billed, Metered Urban Water Consumption (excl. CoCT) Mm^3	Billed, Metered Urban Water Consumption (incl. CoCT) Mm^3
July 2010	2.93	20.62
August	2.83	19.23
September	2.90	19.17
October	3.02	20.46
November	3.35	20.90
December	3.64	24.73
January	4.28	27.89
February	4.55	28.13
March	4.69	26.36
April	4.64	21.43
May	3.95	24.27
June 2011	3.26	19.96
Total	44.04	273.15

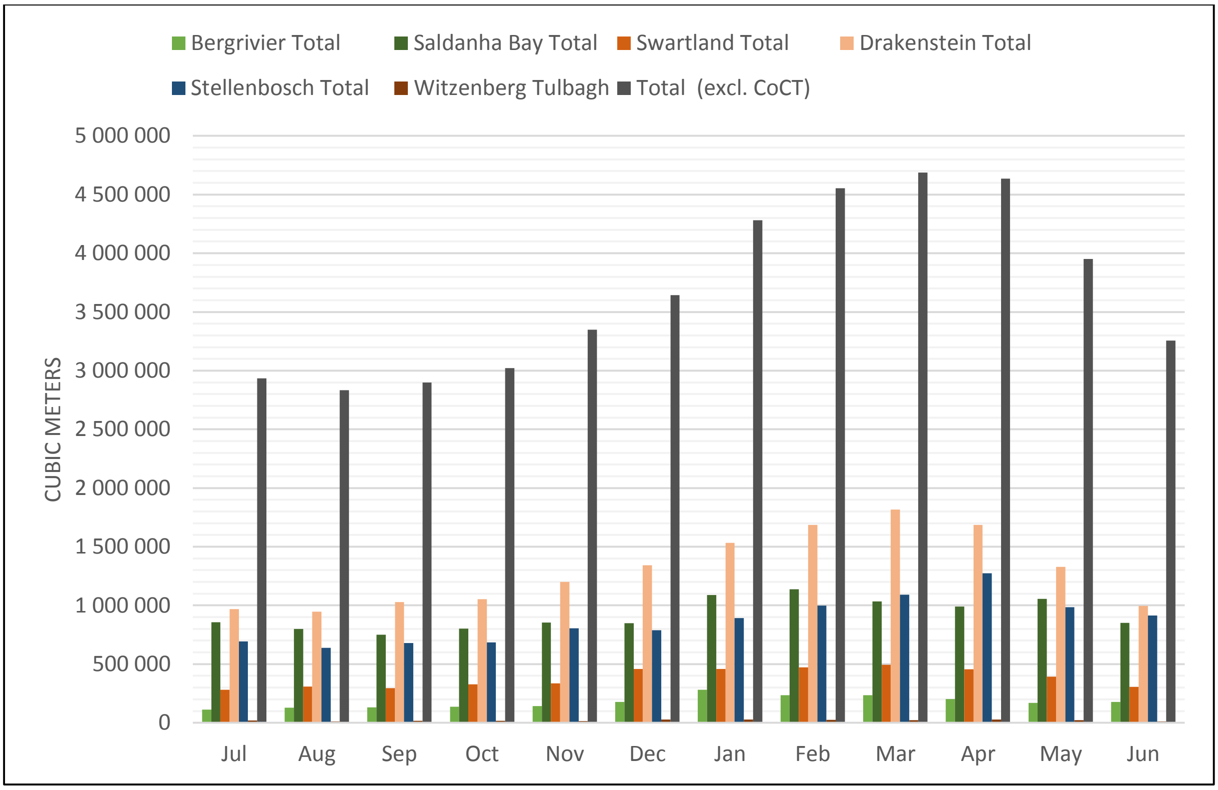

Figure 6.1: Total monthly billed metered consumption by municipality, excluding the City of Cape Town (Source: Bergrivier, Saldanha Bay, Swartland, Drakenstein, Stellenbosch & Witzenberg municipalities).

System input volume, or total treated raw water pumped into the reticulation system from various sources, followed a similarly seasonal trend, although the peak months preceded those of the metered urban consumption rates by one to two months (*Table 6.2*, *Figure 6.2*). This may be due to pre-emptive refilling of reservoirs in order to accommodate known consumption behaviour.

Table 6.2: Monthly system input volume (total raw water supplied), including and excluding the City of Cape Town, from July 2010 until June 2011. Months with the lowest consumption rates are highlighted in blue, while months with the highest consumption rates are highlighted in orange (source: Bergrivier, Drakenstein, Stellenbosch, Swartland and Saldanha Bay municipalities, City of Cape Town Metro (2015)).

Month	System Input Volume (excl. CoCT) Mm^3	System Input Volume (incl. CoCT) Mm^3
July 2010	3.25	25.88
August	3.54	27.93
September	3.47	28.47
October	3.82	31.51
November	4.19	32.65
December	4.58	36.96
January	5.82	40.46
February	5.55	37.31
March	4.98	38.27
April	4.81	32.30
May	3.88	28.74
June 2011	3.72	27.40
Total	51.61	387.88

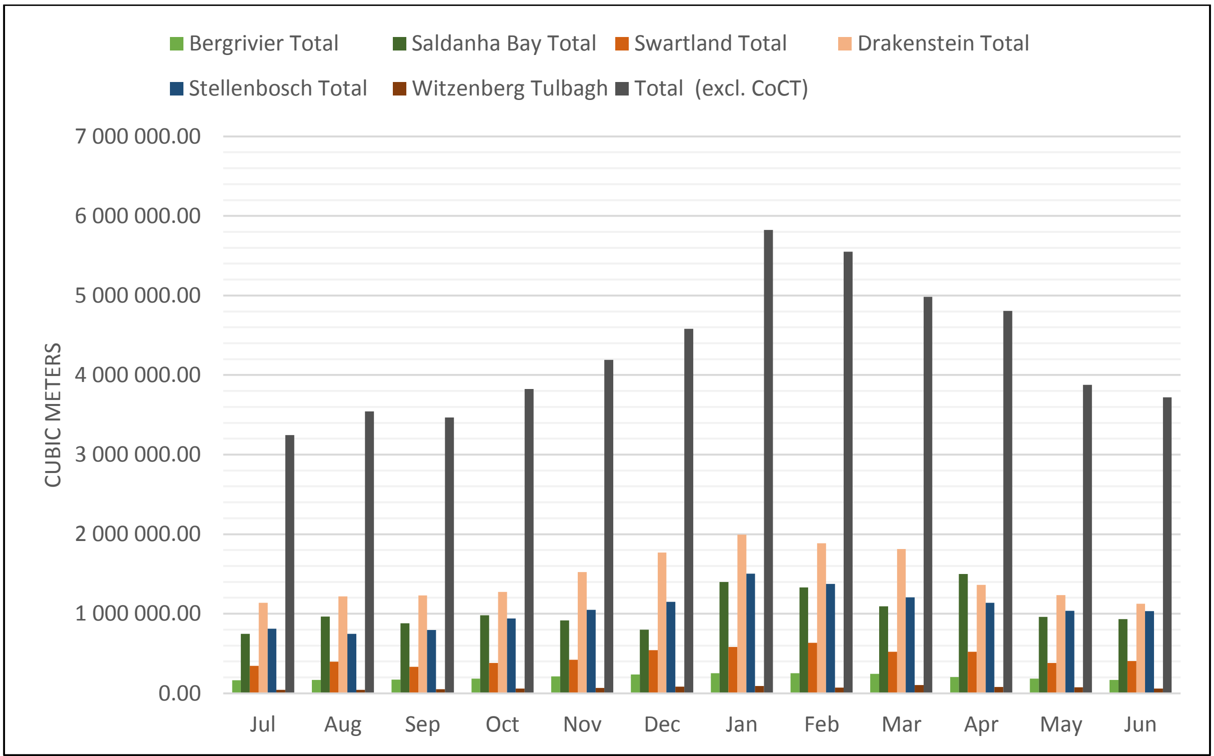

Figure 6.2: Monthly system input volume by local municipality, excluding the City of Cape Town (Source: Bergrivier, Saldanha Bay, Swartland, Drakenstein, Stellenbosch & Witzenberg municipalities)

Crop irrigation water requirements were calculated using field sizes and the methodology outlined in the previous chapter. *Table 6.3* presents a summary of various crop types and their calculated annual irrigation water requirements, as well as the estimated amount of effective rainfall received by each crop type and the percentage of total water needs met as a result of effective rainfall.

Table 6.3: Summary of the irrigation water requirements of irrigated crops found in study area, including the percentage of water requirements resulting from effective rainfall (i.e. green water). Other Crops include sub-tropical fruit, herbs, prickly pears, nuts, pepo and oil seeds (Source: DoA Elsenberg (2013), own calculations).

Crop Types	Area Cultivated (ha)	Evapotranspiration (Mm^3)	Effective Rainfall (Mm^3)	Irrigation (Mm^3)	Green Water (%)
Other Crops	1.27	0.01	0.00	0.01	6
Sub-Tropical Fruit	1.52	0.02	0.00	0.01	22
Herbs	5.35	0.03	0.01	0.02	22
Prickly Pears	8.59	0.06	0.02	0.04	35
Nuts	5.69	0.08	0.01	0.06	16
Oil Seeds	42.55	0.22	0.07	0.15	31
Pepo	24.88	0.18	0.01	0.16	8
Grains	2 715.22	6.56	5.68	0.86	87
Berries	324.16	2.78	0.67	2.07	24
Pome Fruit	1 540.21	12.02	3.51	8.32	29
Vegetables	835.30	11.26	1.03	9.77	9
Planted Pasture	1 552.81	12.24	1.81	10.17	15
Tree Fruit (Other)	1 400.60	14.37	3.49	10.63	24
Citrus	1 641.46	19.54	4.92	14.29	25
Grapes (Table)	4 726.74	42.52	7.00	34.73	16
Stone Fruit	7 246.73	55.49	13.30	41.24	24
Grapes (Wine)	52 827.46	442.57	108.99	325.52	25
Grapes (All)	57 554.20	485.09	115.99	360.79	24
Total:	74 900.54	619.95	150.54	458.60	26

Grape farming was found to have the highest consumption of irrigation water in the study area, with wine grapes making up roughly 90% of total irrigated grape water demand *Figures 6.3 & 6.4* visualise relative crop water requirements in terms of actual and normalised irrigation water demand, respectively. Winter grains were found to have by far the highest relative percentage green water footprint of any irrigated crop, with vegetables having the lowest.

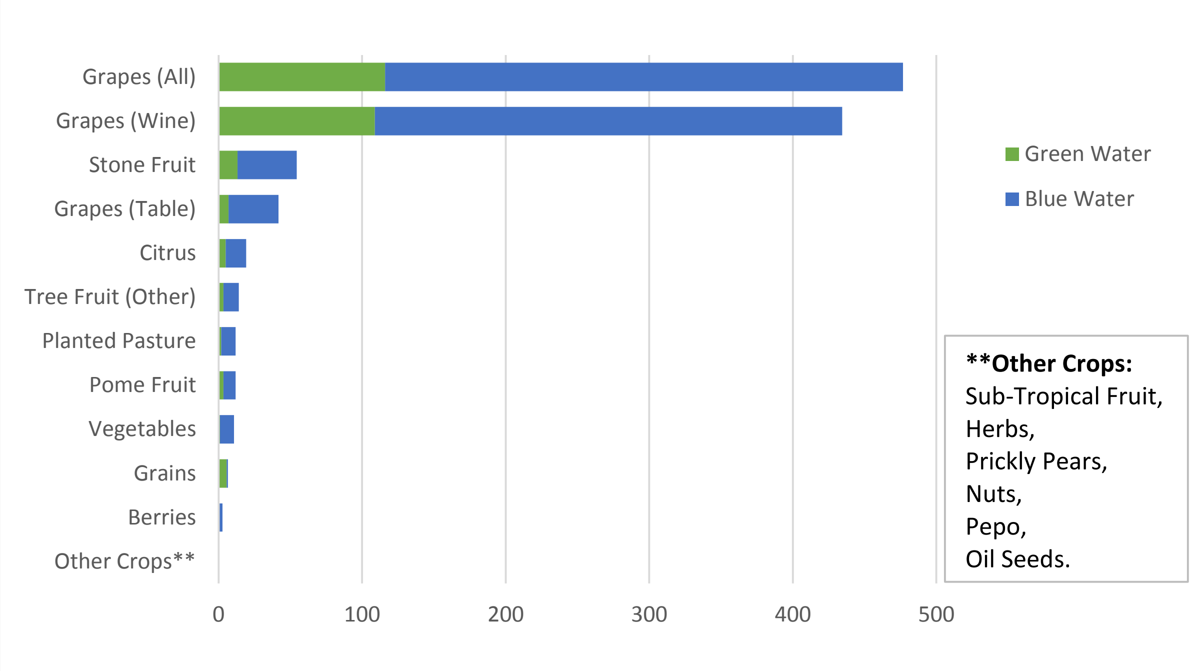

Figure 6.3: Relative green (rainwater) and blue (surface and groundwater) water requirements per irrigated crop type (source: own calculations).

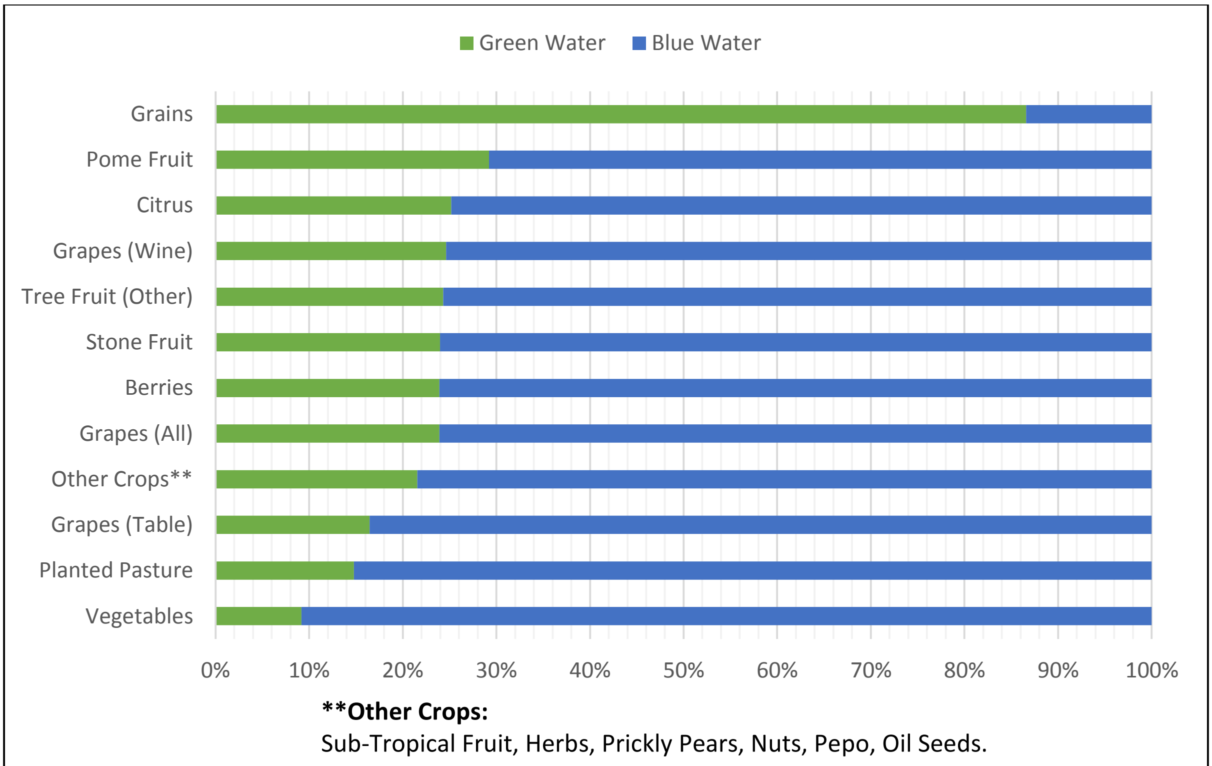

Figure 6.4: Green (rainwater) and blue (surface and groundwater) water requirements as a percentage of total crop water requirements (source: own calculations).

Wine grapes were found to have a higher percentage green water footprint than table grapes. Having a far larger area under cultivation, this is likely due to the distribution of wine grapes which may maximise rainwater efficacy. Teixeira *et al.* (2007) estimated evapotranspiration from water and energy balance measures for wine and table grapes in the Sao Francisco river basin. Their findings suggested additionally that wine grapes would in general require more water than table grapes due to longer crop development stages. In this study, however, no distinction was made between the lengths of developments stages for differently purposed grapes.

Monthly evapotranspiration rates were found to follow strong seasonal trends, as may be expected (*Figure 6.5*). Planting dates as well as marked changes in temperatures and rainfall related to seasonal shifts produced a significantly higher total evapotranspiration during summer months than during winter months, while planting dates for winter wheat in fall contribute to a late increase in total evapotranspiration. Calculated irrigation requirements fell to zero during the winter rainfall season, as the cumulative evapotranspiration rates for the study area decrease significantly while rainfall increases.

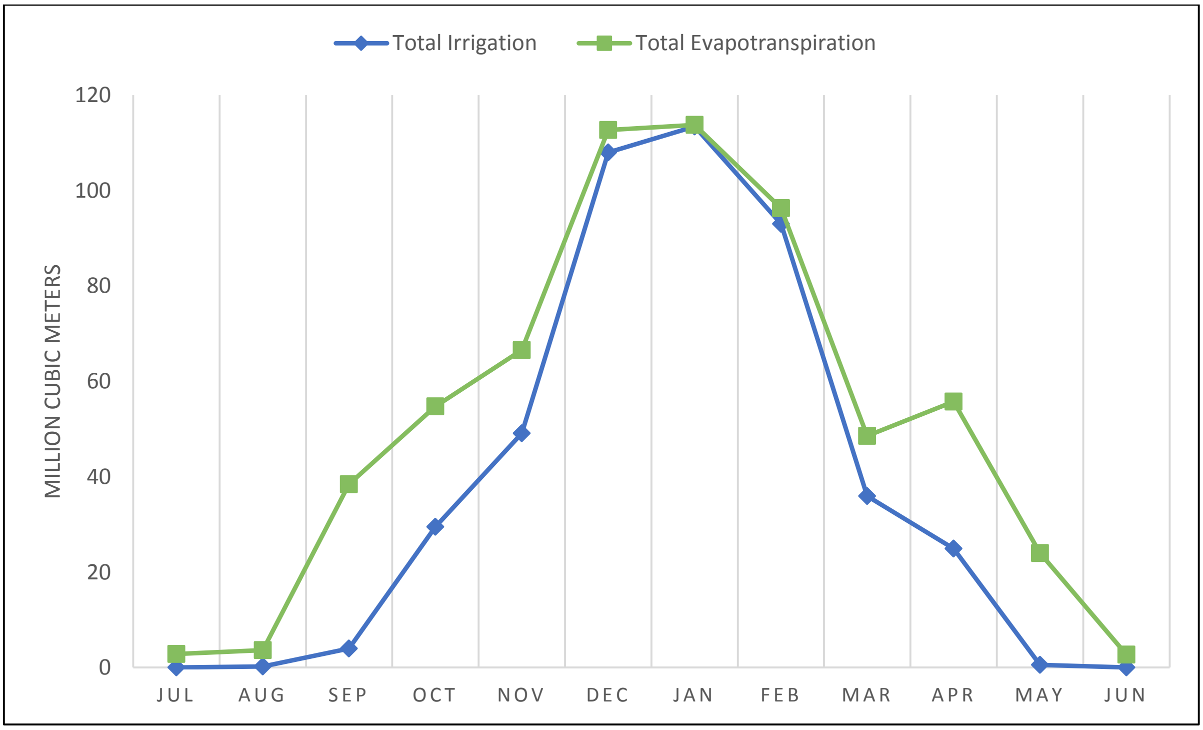

Figure 6.5: Monthly irrigation requirements compared with monthly potential evapotranspiration for all irrigated crops in the study area (source: own calculations).

Table 6.4 contains a summary of total water consumption by type for the baseline dataset using calculated irrigation requirements, based on irrigated crops captured in 2013 and municipal water use and supply records for July 2010 to June 2011. Irrigation was found to be the highest single water user, while combined urban water use was found to make up less than half of total water consumption. Industry was found to be the lowest user of water in the study area. *Figure 6.6* shows the relative consumption of water by type, with annual irrigation demand broken down by specific crop types for reference.

Table 6.4: Summary of water consumption by type (source: own calculations, Bergrivier, Drakenstein, Stellenbosch, Swartland and Saldanha Bay municipalities, City of Cape Town Metro (2015)).

Water Use Type	**Water Requirements 2010/11 and Modelled Irrigation (Mm^3)**
Irrigation	458.60
Urban Residential	184.35
Commercial/Industrial	61.33
Other (including municipal and unaccounted for water)	49.97
Total	754.25

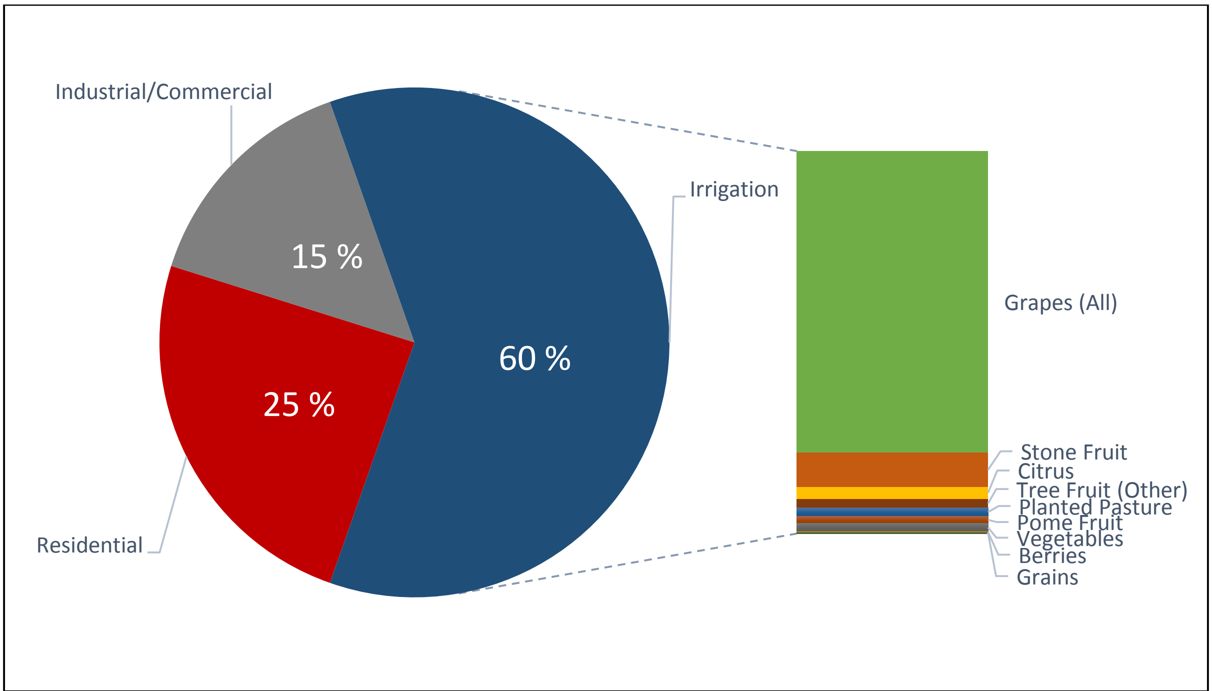

Figure 6.6: Relative water demand for main sectors (source: own calculations, Bergrivier, Drakenstein, Stellenbosch, Swartland and Saldanha Bay municipalities, City of Cape Town Metro (2015)).

Irrigated agriculture was found to use 60% of total water demand, the majority of which is used for viticulture. Stone fruit was found to be the second highest user of irrigation water. Commercial and other water uses, including municipal and unaccounted for water, were found to make up 38% of urban water use, and 25% of total water use. Residential water use made up 62% of urban water use, and 15% of overall water use.

When separated by local municipality, water consumption within the study area showed a variety of distributions between water use types. *Figure 6.7* shows a comparison between residential water use, commercial water use (including water supplied by water services providers and individually licensed abstractions) and calculated irrigation requirement for each municipality within the study area as a percentage of total use.

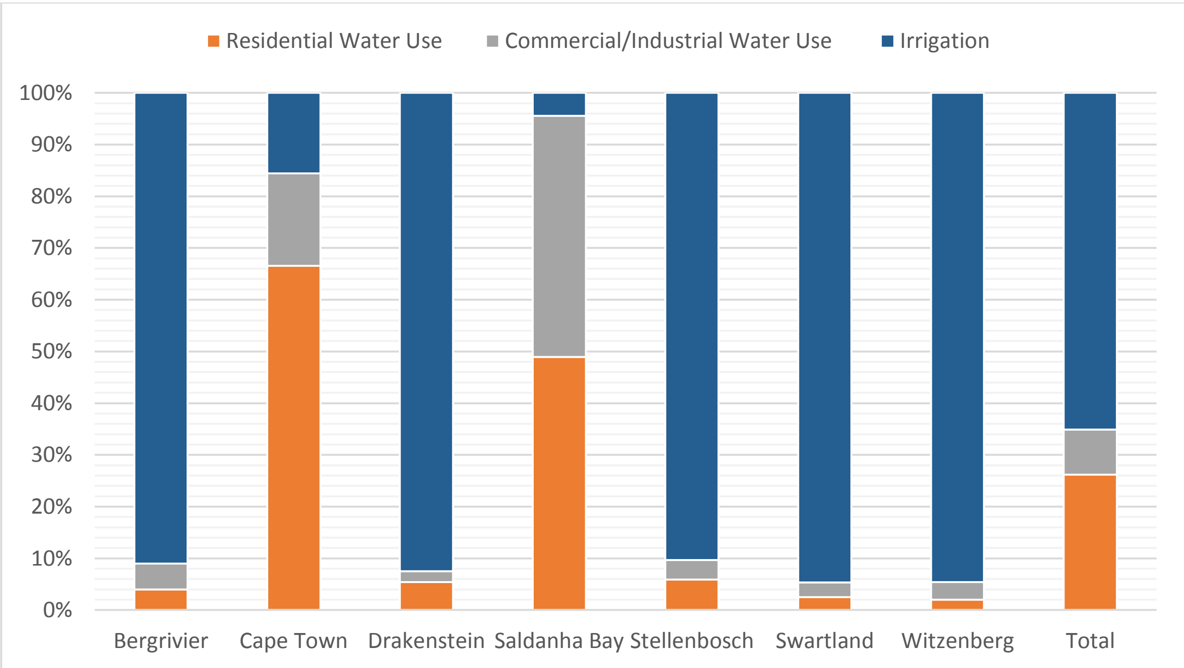

Figure 6.7: Water use per sector as a proportion of total use, by municipality (source: own calculations, Bergrivier, Drakenstein, Stellenbosch, Swartland and Saldanha Bay municipalities, City of Cape Town Metro (2015)).

Municipalities with high urban populations were found to have a high ratio of urban water use to irrigation water use, such as in the case of the City of Cape Town and Saldanha Bay, while municipalities with large areas of irrigated agriculture showed a dramatic decrease in the ratio of urban water use to irrigation water use. Bergrivier, Swartland and Witzenberg were found to have the lowest ratio of urban water use to irrigation water use, possibly due to largely rural populations and moderate rates of irrigated agriculture activities.

A comparison of the monthly changes in total urban supply, total billed metered consumption and total irrigation water use revealed that a peak around the middle of summer – between December and February – persists in all three datasets, although irrigation requirements produce a far steeper curve with a more rapid increase and more abrupt decrease in water requirements than urban water demand (*Figure 6.8*). Between November and March the total irrigation requirements calculated were found to surpass the total urban water requirements in the study area.

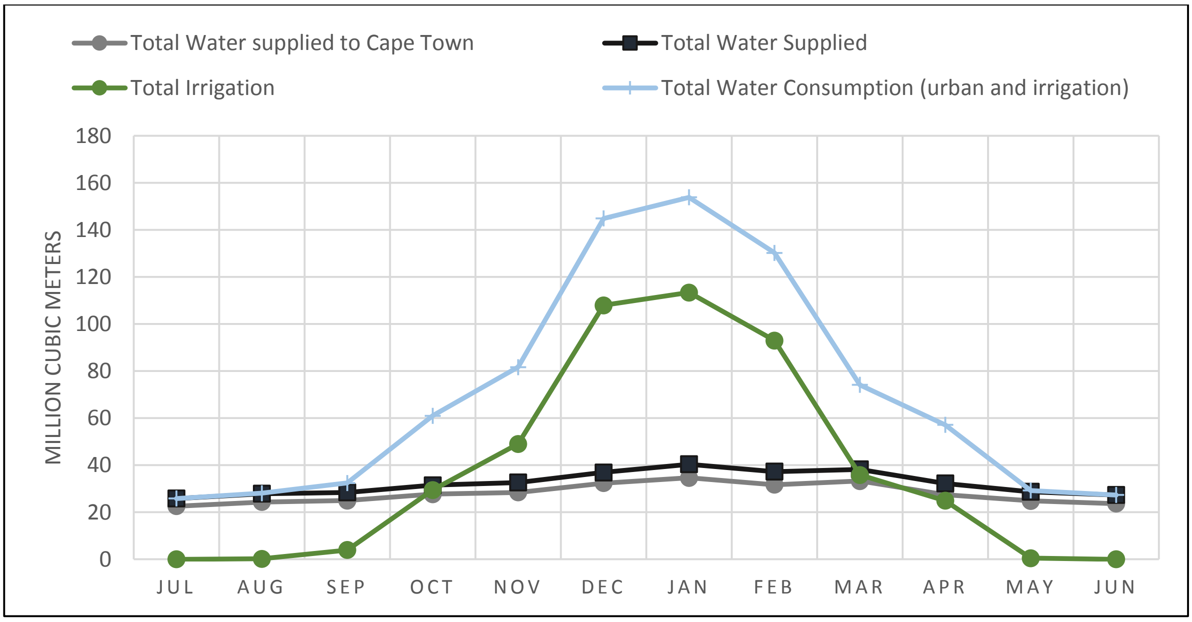

Figure 6.8: Monthly total water consumption (calculated as irrigation requirements plus total system volume) as well as water requirements by type with the City of Cape Town shown separately for reference (source: own calculations, Bergrivier, Drakenstein, Stellenbosch, Swartland and Saldanha Bay municipalities, City of Cape Town Metro).

A comparison of water allocation from the West Coast Water Supply System and various water demands revealed that the City of Cape Town used significantly less water than is allocated to it during 2010/2011, while irrigation demand and total water demand outside of Cape Town (including urban water use and irrigation water use) exceeded allocations by significant amounts (*Figure 6.9*).

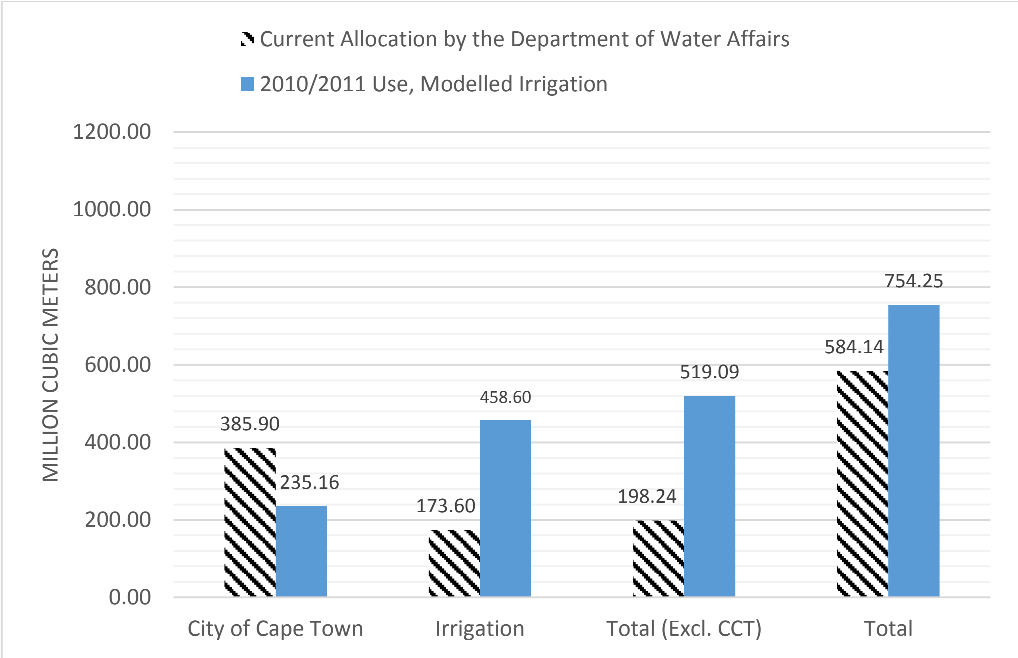

Figure 6.9: Comparison of urban water use from calculated irrigation requirements and 2010/2011 data records with water allocations from the West Coast Water Supply System (Source: own calculations, DED&T (2015a), Bergrivier, Drakenstein, Stellenbosch, Swartland and Saldanha Bay municipalities, City of Cape Town Metro (2015))

The demand calculated for irrigated agriculture exceeded the allocated amount by 285 million cubic meters, or 164%. This may be due to the assumption of the generalisation of irrigation practices (for example, assuming all wine grapes are produced in the same way for all areas). The total demand, excluding the City of Cape Town, exceeded its allocated amount by 320.85 million cubic meters (161%).

Figures 6.10 & 6.11 show the spatial distribution of total water demand, excluding the City of Cape Town. *Figure 6.10* is a choropleth representation of the data using 2011 census Main Places as the enumeration unit, while *Figure 6.11* is a dasymetric representation of the same dataset based on 30 m x 30 m resolution land use data and rasterised irrigated fields.

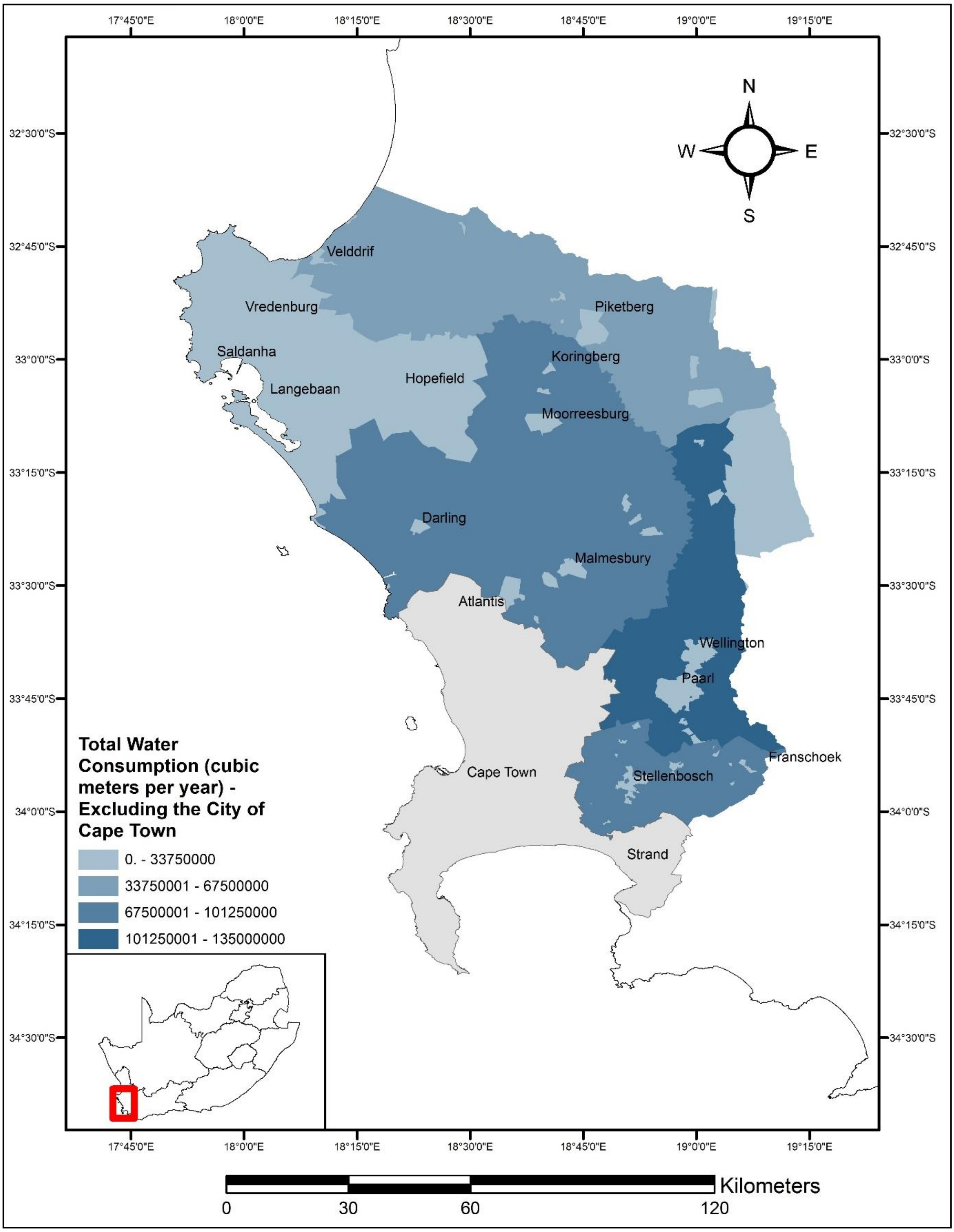

Figure 6.10: Choropleth baseline water consumption map of Main Places in the Berg WMA, comprised of calculated irrigation demand and urban billed metered consumption from 2010/2011 data records, excluding the City of Cape Town.

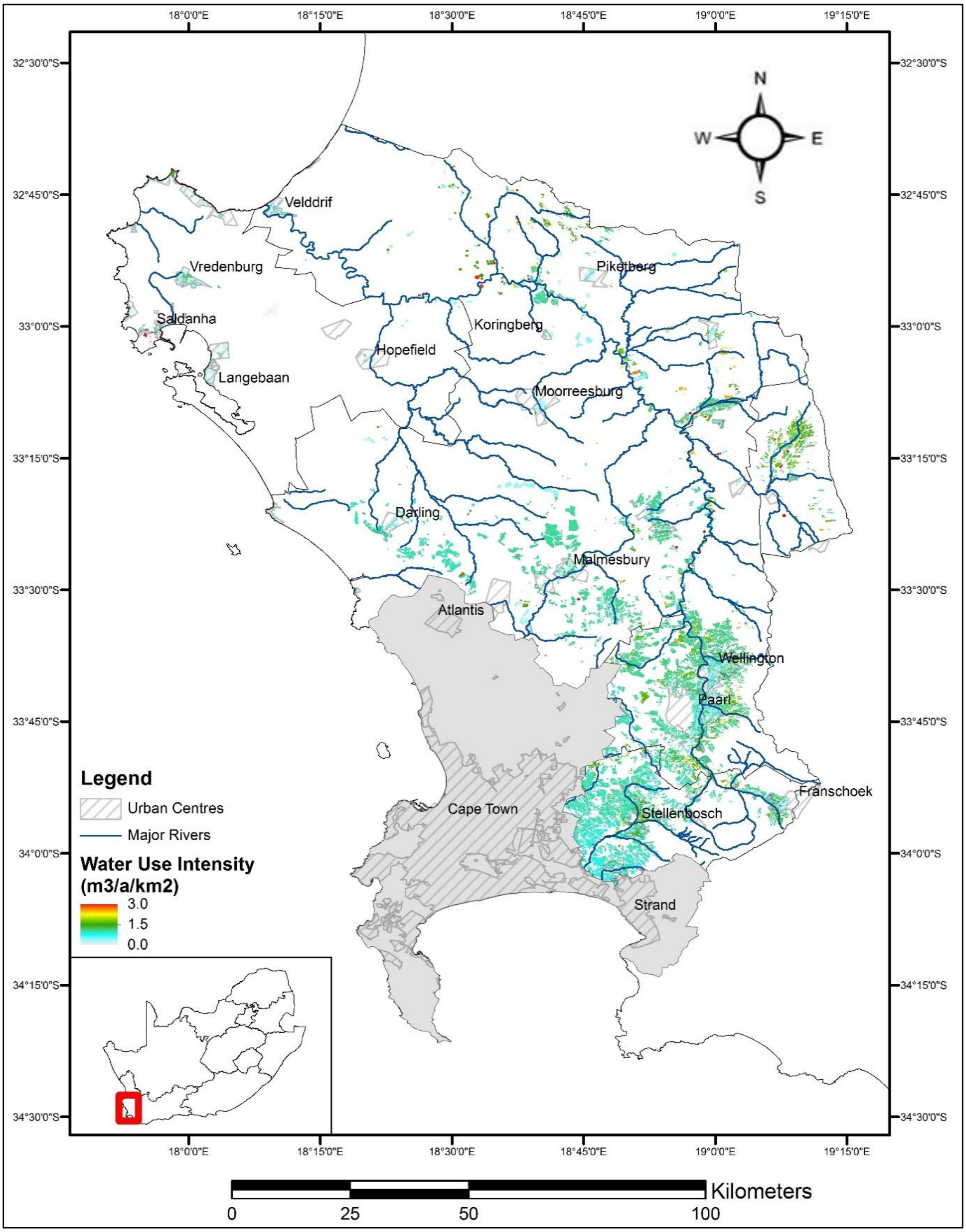

Figure 6.11: Dasymetric baseline water consumption intensity map of the Berg WMA comprising of calculated irrigation demand and urban billed metered consumption from 2010/2011 data records, excluding the City of Cape Town.

An advantage of the choropleth map is that the relative water consumption within each Main Place is readily comparable to that of any other Main Place, depending on the classification of the symbology. In this example four classes were chosen which allows for all Main Places to be clearly distinguished from one another based on relative water consumption. However, the internal distribution of water use is not apparent from the choropleth method.

The dasymetric approach produces a far more realistically appearing map, from which not only the relative water use intensity can be visually evaluated, but also the distribution of water use activities throughout the study area. Due to the spatially dispersed nature of the water use activities, however, additional information needed to be added to the map to aid in spatial referencing. This presented a challenge, as additional features could easily obscure smaller coincident water use activities.

While the advantages of dasymetric mapping are significant, the additional time and resources required as well as the visualisation challenges inherent in resolving and displaying small details make it inaccessible as a technique for geoinformation scientists with limited resources. It should perhaps not be considered a replacement for choropleth mapping, but rather a complimentary solution. The use of dasymmetry as an intermediary for aerial interpolation, however, makes it a useful tool for on the fly visual restructuring of data by increasing levels of aggregation.

Figure 6.12 shows the ratio between mean annual runoff and calculated irrigation requirement for each quaternary catchment in the Berg WMA.

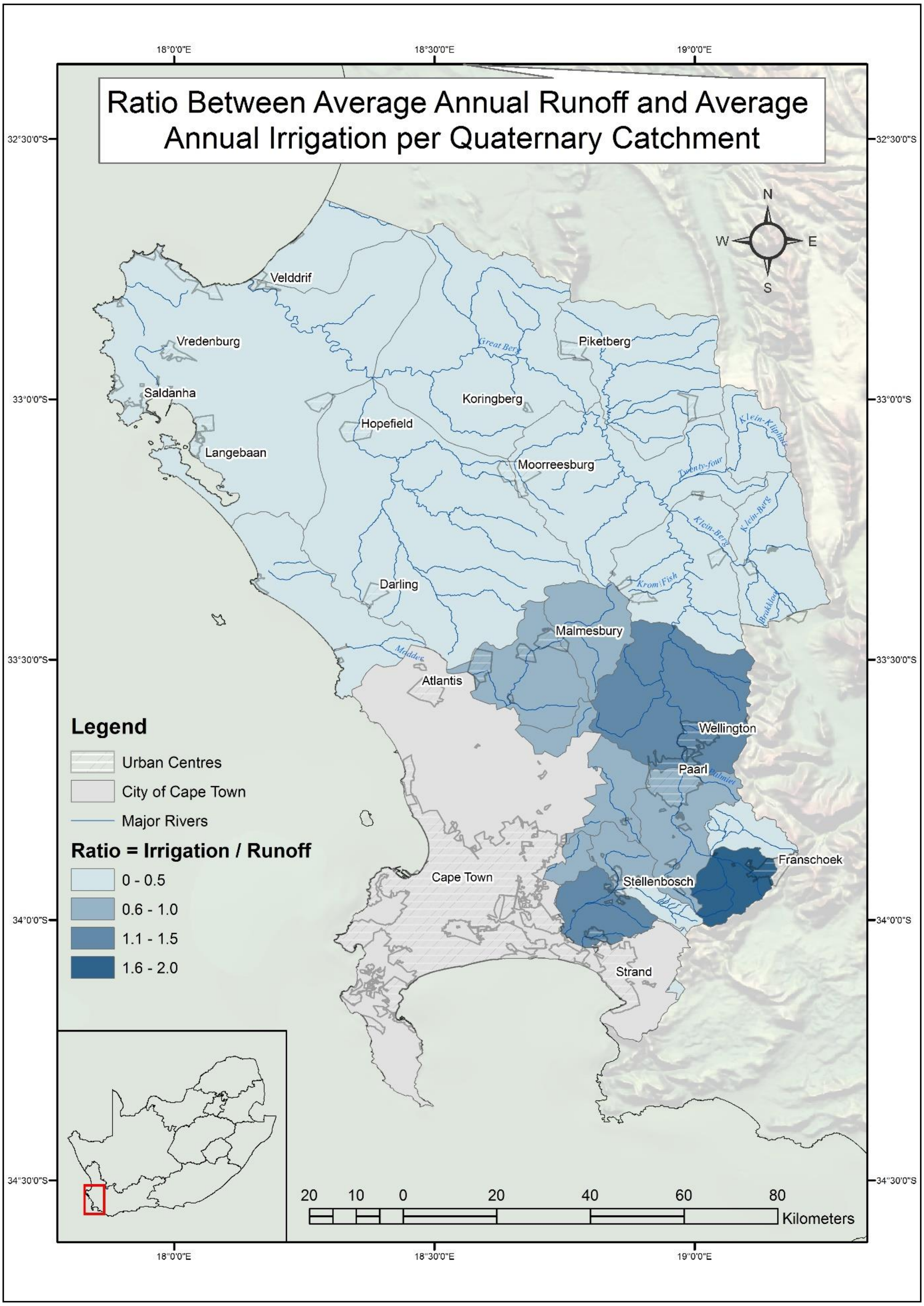

Figure 6.12: Ratio between calculated irrigation requirements and average annual runoff per quaternary catchment (Sources: DWAF, own calculations).

6.2 Future Scenarios

Based on predetermined and reported population growth rates (*Table 6.5*) urban residential water demand was calculated, using current per-capita water consumption estimates calculated from census 2011 population figures and 2010/11 total system volume figures (*Table 6.6*).

Table 6.5: Reported growth rates and estimated population growth rates associated with low, medium and high growth excluding economic development (Source: DWS, StatsSA (2012)).

Municipality	Town(s)	Currently Observed Growth Rate (%)	Low Growth Scenario Rate (%)	Medium Growth Scenario Rate (%)	High Growth Scenario Rate (%)
Bergrivier	Aurora	5.50	0.99	2.10	3.69
Bergrivier	Dwarskersbos	3.50	0.00	0.60	1.43
Bergrivier	Piketberg, Goedverwacht, Wittewater	2.00	1.01	1.95	3.52
Bergrivier	Porterville, De Lust, Beaverlac	1.50	1.01	2.16	3.54
Bergrivier	Velddrif	5.00	1.01	2.33	4.11
Drakenstein	Gouda	2.00	0.03	2.02	4.02
Drakenstein	Paarl, Wellington, Simondium, Water-Vliet, Val De Vie	3.00	1.02	2.18	3.41
Drakenstein	Saron	1.50	0.00	1.78	3.38
Saldanha Bay	Hopefield	2.80	0.00	0.67	1.04
Saldanha Bay	Langebaan	8.00	0.51	1.29	2.50
Saldanha Bay	Saldanha	4.00	3.23	5.65	8.30
Saldanha Bay	St Helena	3.50	0.51	1.46	2.87
Saldanha Bay	Vredenburg, Jacobsbaai, Paternoster, Louwville	4.00	0.76	1.29	1.90
Stellenbosch	Franschhoek, La Motte, Groendal	3.00	1.50	2.96	4.43
Stellenbosch	Klapmuts	4.50	0.85	1.84	2.88
Stellenbosch	Pniel, Kylemore, Groot-Drakenstein, Dwarsrivier	3.50	0.51	1.46	2.95
Stellenbosch	Stellenbosch, Elsenburg, Raithby, Lynedoch	2.00	0.74	1.63	2.54
Swartland	Darling, Grotto Bay	2.00	0.50	1.01	1.52
Swartland	Koringberg	4.00	0.50	1.18	2.19
Swartland	Malmesbury, Chatsworth, Abbotsdale, Kalbaskraal	4.50	0.50	1.11	2.53
Swartland	Moorreesburg, Klipfontein	4.00	0.50	1.62	2.87
Swartland	Riebeek Kasteel	7.00	0.51	0.94	1.39
Swartland	Riebeek West	6.00	0.25	0.76	1.32
Swartland	Yzerfontein	4.00	0.00	0.77	1.15
Witzenberg	Tulbagh	3.00	0.60	1.50	3.00

Table 6.6: Baseline residential water requirements and future projected residential water requirements based on population growth scenarios for urban areas in the Berg excluding CoCT (Sources: DWS, All Towns Reconciliation Strategies).

	Year	Total Urban Population	Total Urban Water Requirements (Mm^3)
Baseline	2011	540 719	60.49
Low Growth Scenario	2025	618 217	64.80
	2040	720 543	76.60
Medium Growth Scenario	2025	719 204	76.31
	2040	1 003 704	111.97
High Growth Scenario	2025	858 583	92.35
	2040	1 494 392	174.36
Currently Observed Growth Rate	2025	857 232	88.17
	2040	1 451 868	149.95

Current growth rates were compared with projected high, medium and low growth scenarios, covering both population growth as well as urban expansion as a result of economic growth, assuming per capita water consumption would not change over time. Water requirements were calculated based per capita consumption rates for each growth scenario (*Figure 6.13*).

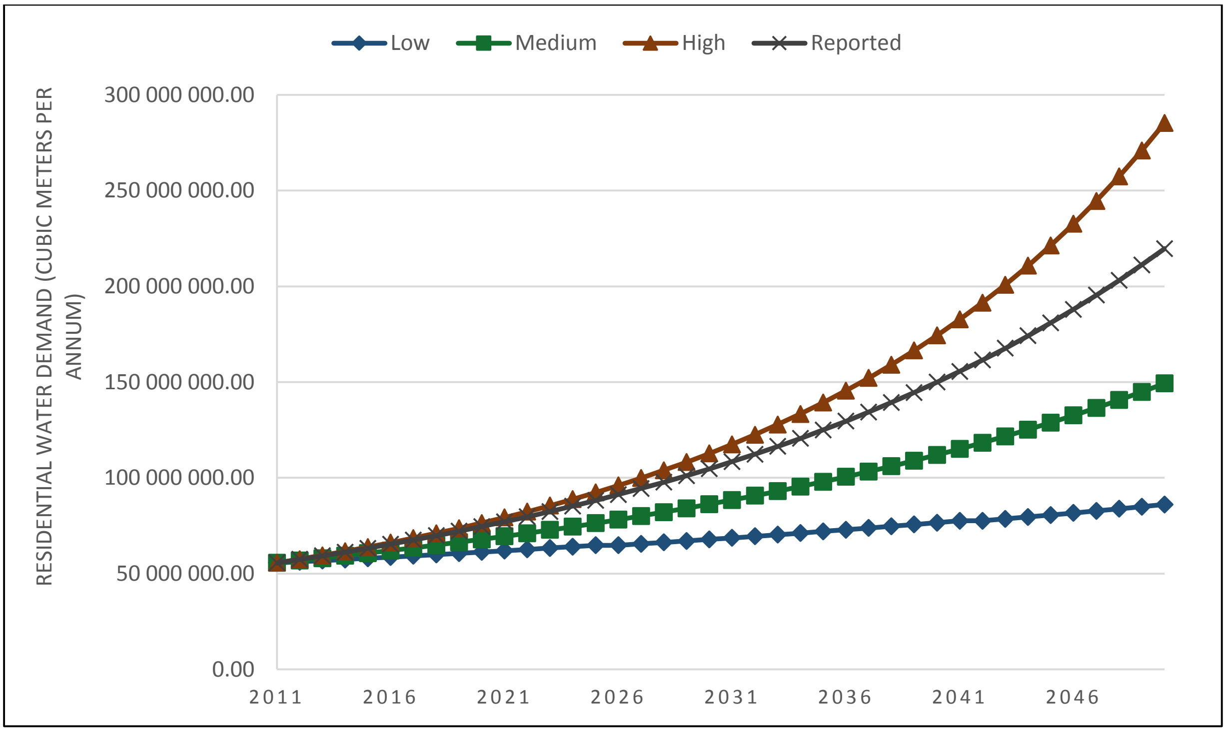

Figure 6.13: Projected residential water requirements based on population growth ignoring economic development (Low, Medium and High) and current observed growth rates (Reported) for all urban areas within the study area excluding CoCT (Source: DWS All Towns Reconciliation Strategies).

Monthly average temperatures, as well as monthly effective rainfall over ten-year periods around 2025 and 2040 were averaged (2020 to 2030 and 2035 to 2045) from the GFDL-ESM2G, BNU-ESM and FGOALS-s2 models for both RCP45 and RCP85 scenarios. The resulting data was used to calculate evapotranspiration and moisture deficit values based on *Equations 15, 16 & 17*. The calibration factors were calculated (*Equation 13*) and the resulting irrigation water demand evaluated.

GFDL-ESM2G (RCP45) was found to predict the lowest irrigation requirements for both 2025 and 2040, while BNU-ESM (RCP85) was found to predict the highest irrigation water use for 2025. BNU-ESM (RCP45) produced the highest requirements for 2040. *Figures 6.14* & *6.15* summarise the results relative to allocation and predicted urban demand.

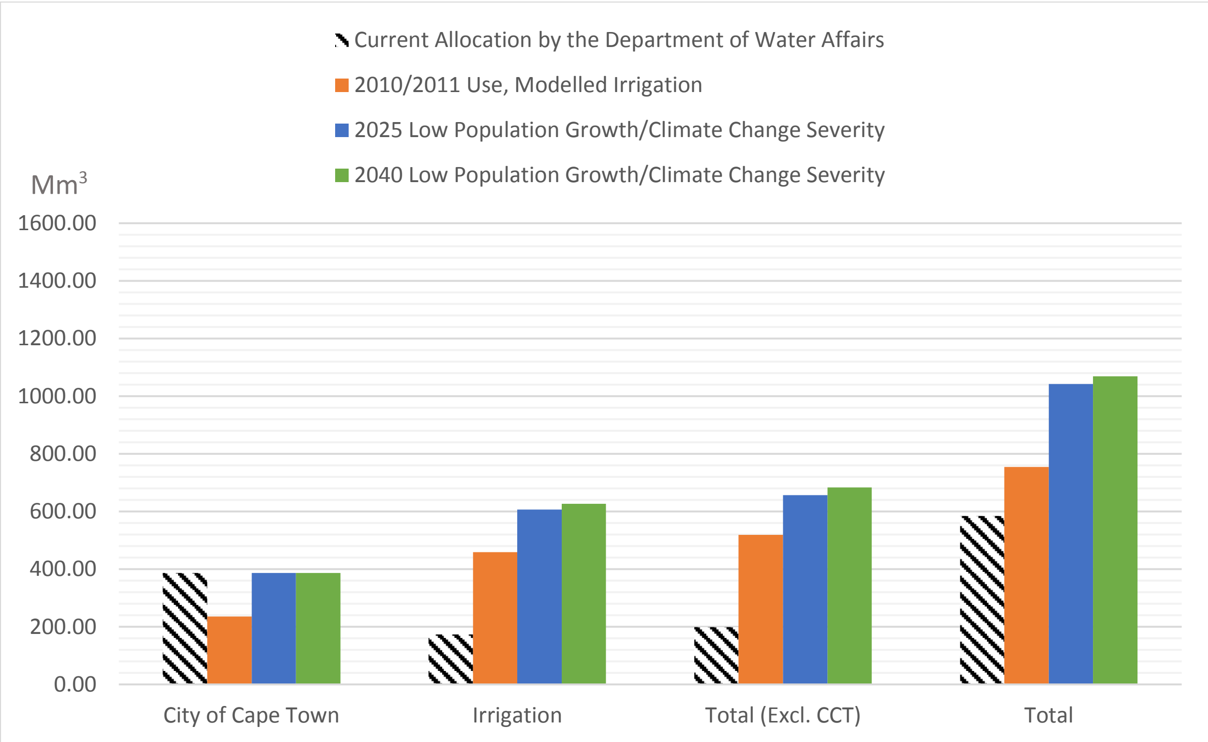

Figure 6.14: Current allocations compared with projected water demand in 2025 and 2040 based on low growth rates and minimal climate change (City of Cape Town not modelled).

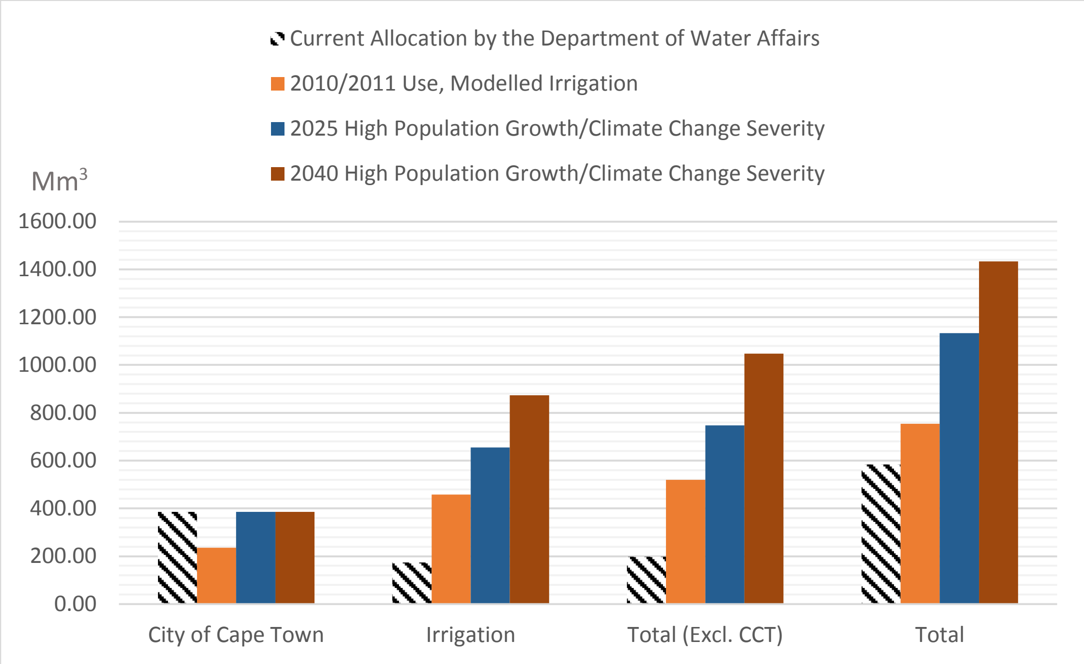

Figure 6.15: Current allocations compared with calculated future water demand in 2025 and 2040 based on high growth rates and severe climate change (City of Cape Town not modelled).

Based on modelled climate data, irrigation demand is predicted to increase by between 20% and 90% by 2040 due only to climatic change. While it seems unlikely for irrigation requirements to double in the next several decades, these findings nevertheless demonstrate overall upward trends in irrigation requirements predicted as a result of anticipated climate change.

One possible reason for the severe increases in irrigation demand is due to the rough spatial scale of the climate model data (55.5 km x 55.5 km), which would potentially obscure phenomena such as orographic lift. As a result much of the irrigated agriculture currently benefitting from rainfall generated in this way would be modelled as though the terrain were homogeneous within the 1.5 degree grid cell, which may include relatively arid and unarable land.

Climate change is likely to influence crop irrigation demand by avenues other than changes in temperature and rainfall, due to factors such as humidity, atmospheric carbon dioxide concentration and wind and cloud conditions, which may individually and interactively influence plant potential evapotranspiration (Adams et al., 1990; Chattopadhyay & Hulme, 1997).

Chapter 7: Conclusions and Recommendations

7.1 Spatial Water Requirements Modelling: A Systems Design Perspective

The model design and data gathering processes present several practical challenges. Chief among the challenges encountered during the design phase of this project was balancing model simplicity with model efficacy. An overly complex model, incorporating many different factors and accounting for many natural and anthropic processes, would compound uncertainties that may be inherent in the datasets from which it is derived within its modelled outcomes, and would require consistent technical expertise and professional insight to interpret and apply successfully.

An overly simplified model, on the other hand, may be easier and faster to design and produce, but may not sufficiently account for the complexity of the system it is modelling, and may therefore not necessarily produce any meaningful results. In addition, the inclusion of more model parameters require sufficiently accurate and complete datasets that can be readily processed, interpreted, parameterised and validated. It is therefore especially important that the expected outcomes of any given project be thoroughly and honestly weighed against any potential practical limitations on that project, such as constraints on data, time or technical expertise, in order to assess and manage expectations.

Close stakeholder involvement in complex system design processes may present a challenge, as the feasibility of any given approach may be uncertain at the outset without a thorough, pre-design feasibility study. Additionally, stakeholders may not necessarily be familiar with the technical aspects of the system under development and may therefore not always be able to contribute direct technical insight during the design process. However, it is nevertheless vital that a close relationship be maintained between the ideas of the stakeholders and the reality of the project itself throughout the various stages of project design and development.

While the regular and direct involvement of non-technical users in the system design process presents a challenge both in terms of accurate and clear communication of user needs and in terms of the timely solidification of the desired outcomes of the project at hand, it nevertheless represents a vital aspect to the developer-user relationship, without which early decisions affecting the course of the project may be made which may jeopardise user satisfaction at a later stage.

It is therefore important and necessary that a structured user requirements analysis take place in conjunction with a complete and thorough feasibility study such that the basic objectives and fundamental aims of the study can be outlined with reasonable confidence and the utmost clarity at the outset. It falls upon the project team to interpret user requirements and solicit feedback on the technical content of the systems design process.

This prevents any potential confusion that may arise and precludes the need to radically alter the design of the system at a later stage. Uncertainty in modelling objectives and purpose hinders the clarity and focus of the core conceptual design phases. Through close user involvement the main aims and objectives can be established with confidence so that the project may move forward. Once the main aims and objectives have been established for the project and are relatively stable, the design process may proceed in accordance with a reasonable project schedule.

The ability of a predefined design path to stabilise and structure project progression is clearly important for both the project team and stakeholders. Accommodating regular feedback and the revision of key project stages ensures that development may occur with relative confidence and prevents an outcome where ultimate user dissatisfaction occurs when the project has run out of time and resources.

7.2 Spatial Water Requirements Modelling: Technical Considerations and Challenges

Water demand mapping requires insight into the various socio-economic activities being modelled, as well as a fundamental understanding of the water supply and allocation status quo within the study area. Basic water requirements mapping can be done using simple techniques and relatively few data inputs, and may be amended and updated with ancillary data and new, complete and/or accurate datasets. However, the uninitiated often may require some level of expert guidance with regards to understanding and navigating specialised datasets.

Modelling water requirements can therefore be a difficult and complex exercise, depending on data availability, accessibility, aggregation and specialisation. Differentiating between sources such as green water and blue water, or surface water and groundwater may further complicate requirements analysis. It is therefore vital that the desired level of detail required to adequately serve the modelling purpose and objectives be identified at the outset.

Urban water use is commonly measured either through direct metering at the user end for billing purposes, or by monitoring and controlling supplied water volume input into the system at key points within the water reticulation structure. As a result total system input volume for a specified urban area is usually known, from which total per-capita water requirements may be derived, if the population supplied of water is also known. Water supply authorities at the local level maintain records of billed metered water use for residential, commercial, as well as municipal consumption. For the purposes of this project, existing municipal water use records were used.

System losses, or unaccounted-for water, may be estimated from total supply by taking the total metered consumption as well as any unmetered consumption and subtracting it from the total system volume. These losses are usually expressed as a percentage of total supplied water. While metered water use may reflect the sector-specific water usage for any given period at a finer spatial resolution, total water supplied takes unbilled and unmetered water uses and losses into account, which provide an accurate picture in terms of effective water consumption, albeit at a large spatial scale.

Ambiguity may persist in urban water use analysis resulting from a variety of sources. Distinguishing between direct residential per-capita use and overall per-capita use including all other avenues of water consumption and loss results in significantly different outcomes when considering the impacts of population growth and economic development on urban water requirements. In addition, during data creation interpretation plays a significant role in determining the level and method of data aggregation as well as the focus and level of completeness of the resulting dataset. This often impacts the clarity and universality of datasets generated within official paradigms.

Commercial water use intensity can vary from small users to large industrial users, complicating the modelling process and inhibiting the ability of a model to predict future use based on current rates. While urban centres may exhibit definite trends in water consumption rates, new developments may not necessarily follow those trends in any reliable or predictable manner.

In addition, new industrial developments may cause abrupt increases in local water consumption, whereas modelled growth may imply a more gradual increase based on growth potential and anticipated change. As a result it may be difficult to predict even short to medium term commercial water demand without some indication of planned developments and their envisioned water requirements.

Irrigation water requirements may be modelled at ever increasing levels of detail and accuracy, depending on the spatial scale of data inputs as well as the number of factors being considered, and is commonly based on water and energy balances.

A raster data structure was found to be the simplest and the most technically efficient basis for a dynamic water requirements model. Vector features were necessary as intermediaries in certain steps during component layer production. The resulting object-based feature classes were readily converted to grid-based datasets of the desired spatial scale.

For small datasets a vector data structure allows for detailed attribute data to be stored for all features. However, for large datasets rendering and storing vector features becomes slow and cumbersome, greatly exacerbated when large tables of attribute data are attached.

One major advantage of grid-based data structures over object-based data structures is that topology can be handled much more simply for any size dataset. Cell size, layer extent and origin points may be set for all datasets such that cells are congruent and overlay operations may readily be performed within a sequential algebraic spatial model.

During validation it was found that modelled irrigation water requirements were significantly lower than official estimates. The reason for this was found to be the result of inaccurate crop factors for certain crops. New crop factors were obtained and the irrigation requirements modelling was repeated. The new crop factors produced irrigation requirements estimates closer to expected results.

One of the challenges encountered during the validation step was in acquiring a comparable dataset. While the datasets used to evaluate crop irrigation requirements were generally accepted to be reasonably accurate, some issues nevertheless arose. The WARMS dataset relies primarily on users directly registering their annual anticipated needs, which is currently still undergoing a verification and validation process. As such, some, or even many of these values may be significantly outdated or otherwise incorrect. With regards to the WRSM data, only data for a portion of the study region – the upper reaches of the Berg River - was obtained, thus limiting the extent of the verification to that region. In order for a model and its components to be thoroughly verified and validated an acceptable standard must therefore first be found.

The nature and impact of water restrictions on urban water use should be investigated in order to account for residential and municipal water use behaviour over time. Research into the correlation between interannual and interseasonal climate variation and residential water use may prove useful for gaining insights into potential future water use.

Differentiating between areas of higher and lower residential water use intensity may be done using water use data compiled for billing purposes at the suburb level. Commercial activities may be divided into high and low water use categories with sufficient knowledge of which commercial activities are located within an area and their respective water use.

Future irrigation requirements should be modelled using climate data with a similar spatial scale to that used for current irrigation requirements modelling in order to ensure consistency and integrity in model outputs.

Reference crop evapotranspiration for future irrigation demand calculated from fewer physical parameters will produce less accurate and therefore less reliable results than reference crop evapotranspiration rates calculated from a wider range of physical parameters. It is therefore recommended that a standard approach be adopted for all irrigation requirements calculations.

The impacts of salinity control and effective rainfall on overall water consumed for irrigation must be thoroughly investigated and clarified. The on farm storage capacity for rainwater runoff should also be considered as it prevents recharging of streams and groundwater elsewhere.

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Appendix A: Assessment of Ethics in Research Projects form

EBE Faculty: Assessment of Ethics in Research Projects (Rev2)

Any person planning to undertake research in the Faculty of Engineering and the Built Environment at the University of Cape Town is required to complete this form before collecting or analysing data. When completed it should be submitted to the supervisor (where applicable) and from there to the Head of Department. If any of the questions below have been answered YES, and the applicant is NOT a fourth year student, the Head should forward this form for approval by the Faculty EIR committee: submit to Ms Zulpha Geyer (Zulpha.Geyer@uct.ac.za; Chem Eng Building, Ph 021 650 4791).
NB: A copy of this signed form must be included with the thesis/dissertation/report when it is submitted for examination

This form must only be completed once the most recent revision EBE EiR Handbook has been read.

Name of Principal Researcher/Student: Marthinus van der Walt Department: EBE – Geomatics

Preferred email address of the applicant: vwlmar012@myuct.ac.za

If a Student: Degree: Master's Supervisor: Dr J. Smit

If a Research Contract indicate source of funding/sponsorship:

Research Project Title: Economic Development in water constrained catchments: A Hydro-Economic water foot-printing model.

Overview of ethics issues in your research project:

Question 1: Is there a possibility that your research could cause harm to a third party (i.e. a person not involved in your project)?	YES	NO
Question 2: Is your research making use of human subjects as sources of data? If your answer is YES, please complete Addendum 2.	YES	NO
Question 3: Does your research involve the participation of or provision of services to communities? If your answer is YES, please complete Addendum 3.	YES	NO
Question 4: If your research is sponsored, is there any potential for conflicts of interest? If your answer is YES, please complete Addendum 4.	YES	NO

If you have answered YES to any of the above questions, please append a copy of your research proposal, as well as any interview schedules or questionnaires (Addendum 1) and please complete further addenda as appropriate. Ensure that you refer to the EIR Handbook to assist you in completing the documentation requirements for this form.

I hereby undertake to carry out my research in such a way that

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

Signed by:

	Full name and signature	Date
Principal Researcher/Student:	Marthinus van der Walt signature removed	2015-09-28
This application is approved by:		
Supervisor (if applicable):	J. Smit signature removed	29/9/15
HOD (or delegated nominee): *Final authority for all assessments with NO to all questions and for all undergraduate research.*	J. Smit signature removed	29/9/15
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.		

ADDENDUM 1:

Please append a copy of the research proposal here, as well as any interview schedules or questionnaires:

ADDENDUM 2: To be completed if you answered YES to Question 2:

It is assumed that you have read the UCT Code for Research involving Human Subjects (available at http://web.uct.ac.za/depts/educate/download/uctcodeforresearchinvolvinghumansubjects.pdf) in order to be able to answer the questions in this addendum.

2.1 Does the research discriminate against participation by individuals, or differentiate between participants, on the grounds of gender, race or ethnic group, age range, religion, income, handicap, illness or any similar classification?	YES	NO
2.2 Does the research require the participation of socially or physically vulnerable people (children, aged, disabled, etc) or legally restricted groups?	YES	NO
2.3 Will you not be able to secure the informed consent of all participants in the research? (In the case of children, will you not be able to obtain the consent of their guardians or parents?)	YES	NO
2.4 Will any confidential data be collected or will identifiable records of individuals be kept?	YES	NO
2.5 In reporting on this research is there any possibility that you will not be able to keep the identities of the individuals involved anonymous?	YES	NO
2.6 Are there any foreseeable risks of physical, psychological or social harm to participants that might occur in the course of the research?	YES	NO
2.7 Does the research include making payments or giving gifts to any participants?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues:

ADDENDUM 2: To be completed if you answered YES to Question 2:

It is assumed that you have read the UCT Code for Research involving Human Subjects (available at http://web.uct.ac.za/depts/educate/download/uctcodeforresearchinvolvinghumansubjects.pdf) in order to be able to answer the questions in this addendum.

2.1 Does the research discriminate against participation by individuals, or differentiate between participants, on the grounds of gender, race or ethnic group, age range, religion, income, handicap, illness or any similar classification?	YES	NO
2.2 Does the research require the participation of socially or physically vulnerable people (children, aged, disabled, etc) or legally restricted groups?	YES	NO
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2.6 Are there any foreseeable risks of physical, psychological or social harm to participants that might occur in the course of the research?	YES	NO
2.7 Does the research include making payments or giving gifts to any participants?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues:

ADDENDUM 4: To be completed if you answered YES to Question 4

4.1 Is there any existing or potential conflict of interest between a research sponsor, academic supervisor, other researchers or participants?	YES	NO
4.2 Will information that reveals the identity of participants be supplied to a research sponsor, other than with the permission of the individuals?	YES	NO
4.3 Does the proposed research potentially conflict with the research of any other individual or group within the University?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues: